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[*Continued on page* (*III*) *of Cover.*

THE DESIGN OF FRACTIONAL HORSE-POWER INDUCTION MOTORS

By N. F. T. SAUNDERS, B.Sc., Associate Member.*

(*Paper first received* 28*th May, and in revised form* 22*nd September*, 1938; *read before* THE INSTITUTION 19*th January, and before the* SOUTH MIDLAND CENTRE 23*rd January*, 1939.)

SUMMARY

There is available to the designer of induction motors a considerable amount of published work, giving both graphical and analytical treatments, which enables designs to be established conveniently and with a high degree of accuracy. This statement, however, does not apply to motors of fractional horse-power output, especially for single-phase working.

In this paper, using analytical methods, the author establishes simple formulae for the performance data required in connection with single-phase motors, together with correction factors which yield accurate results. Similar correction factors, applicable to the simple formulae commonly used in the design of polyphase motors, are also given. These correction factors are based on the conditions generally existing in fractional horse-power motors, which differ considerably from those found in large machines.

The paper also includes recommendations regarding the active material required and its proportions, and a method for determining slot ratios which are relatively free from cogging and noise.

Stator windings having a sinusoidal space distribution, and the calculation of stator end-winding length and projection, are also dealt with.

(1) INTRODUCTION

From the evidence of published work on the subject the methods employed in the design of induction motors appear to have been evolved from the study of large machines. When those methods are applied to the design of fractional horse-power (f.h.p.) motors, the results obtained are not very satisfactory. Graphical methods, except possibly for very large machines, are not now popular. The majority of designers probably use a mathematical process based on the method of inversion. For practical use, the formulae are simplified by making assumptions, as by neglecting certain small quantities, or by taking as constant certain quantities which, in fact, vary slightly. A considerable degree of accuracy is attained by using these simplified formulae in conjunction with correction factors, as described by Hoseason.† Similar mathematical methods are quite suitable for f.h.p. machine design, provided the simplified formulae and correction factors used are based on appropriate assumptions.

It happens, also, that because in large sizes single-phase induction motors are comparatively rare, there is very little published work on the practical design of this type. To the designer of f.h.p. machines this is a serious matter, since in this range single-phase motors are of great importance.

It is interesting to note that the single-phase induction motor appears to have an extraordinary fascination for the theorist. Very many papers have been published on the theory of this machine, many of them exhibiting mathematical ingenuity of a high order, but it is doubtful whether any of them contribute anything either additional to, or in elucidation of, the original works of Steinmetz.

The object of this paper is to discuss in detail the practical design of f.h.p. induction motors, with special reference to the single-phase type. Simplified formulae are given, together with correction factors appropriate to this class of machine. For the sake of brevity, familiar calculations, such as that required to establish the ampere-turns, are omitted. Finally, design sheets are given, which are arranged specially to suit f.h.p. motors.

(2) GENERAL CONSIDERATIONS

The principal factors involved in the design of f.h.p. induction motors are the following:—

(*a*) For standard and general requirements it is usual to design the machine as a single-phase motor, and then to adapt it to polyphase circuits. Nevertheless, as will be seen, the fact that it will be required to serve as a polyphase motor has to be borne in mind throughout the process of design.

(*b*) In single-phase motors for general requirements, starting torque and overload capacity are of primary importance, and efficiency and power factor are generally regarded as of secondary importance. The limitation is usually temperature-rise, which, in turn, is governed by size.

(*c*) The majority of machines are required to operate at 1 500 r.p.m. synchronous speed (i.e. 4 poles, 50 cycles per sec.). It is therefore usual to proportion standard designs to give round ratings (i.e. $\frac{1}{8}$, $\frac{1}{6}$, $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$ h.p.) at this speed with the maximum economy in material, and then to use the same frames, with modified stampings—if necessary, or economically allowable—for the most suitable ratings at other speeds.

(*d*) The modern tendency is to demand silent running, and the steps necessary to eliminate noise of electrical origin represent one of the most important factors in design.

(*e*) The perfecting of enamel-covered wire has had an important influence on the design of small motors. Such wire is now used almost exclusively for f.h.p. stators.

(*f*) Proportions are influenced by standardization requirements, and by such practical considerations as the minimum bore through which an operator can conveniently pass the hand when winding.

(*g*) Several different starting methods for single-phase motors are in use. The most recent to become popular is the capacitor-start, the development of which is due to the advance in the technique of electrolytic condensers.

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* Coldair Ltd.

† *Journal I.E.E.*, 1925, vol. 63, p. 280.

(*h*) The above factors refer to machines for what may be described as standard requirements. In addition, there are many instances where the motor is designed for a particular purpose and may, in consequence, be quite unsuitable for any other application. An example of this is the high-speed machine-tool motor operating from a high-frequency supply.

The increasing diversity in the applications for which small motors are required, and the severity of the operating conditions, together with the invariable demand for low manufacturing cost, necessitate accurate design methods which may be used with confidence in place of the trial-and-error procedure so prevalent in the past.

(3) ACTIVE DIMENSIONS

The D^2L value, in inch units, required for a given horse-power in the case of a pure split-phase motor (i.e. with no condenser) for 4 poles, 50 cycles per sec., and any voltage up to 250 volts, may be taken as:—

$$D^2L \text{ (cubic inches)} = 25 + (162 \times \text{horse-power}) \quad . \quad (1)$$

where D and L refer to the outside dimensions of the stator laminations.

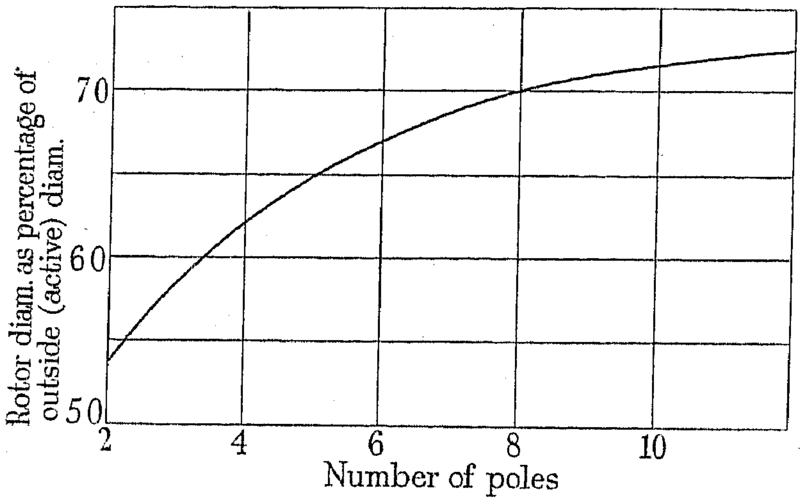

Fig. 1

It is quite usual to employ the same laminations for 4 and 6 poles, and in some cases also for 8 poles. For 2 poles the gap diameter may be reduced, subject to the fact that about 2⅝ in. is the minimum convenient bore for winding. For 8 or more poles the gap diameter is usually increased, but, if so, the diameter chosen may be a compromise between the ideal dimension for 8 and 10, or 8, 10, and 12 poles, depending on the demand which is anticipated for these numbers of poles.

Fig. 1 gives recommended ratios of gap diameter to outside diameter for various numbers of stator poles. It is recommended that in 4-pole designs the radial air-gap should be about 0·35 % of the rotor diameter. In 2-pole machines it should be 0·50 %; it may be decreased to 0·25 % for 8 poles, and so on. For instance, a single-phase ceiling fan motor having 28 poles might have an air-gap of only 0·13 % of the rotor diameter. As a general rule it may be taken that the radial air-gap should be

$$\text{Gap} = 0{\cdot}007 \times (\text{Rotor diam.}) \times \sqrt{\left(\frac{1}{2p}\right)} \quad . \quad (2)$$

where p is the number of pole pairs for which the stator is wound.

The outside diameter of the motor and the height of centres are usually fixed by commercial considerations. The outside diameter of the stator laminations will then depend on the thickness of the shell (if any) and whether an air space is to be provided between them and the shell, for ventilation purposes.

The latest practice is to use a rolled-steel shell or die-cast shell of comparatively thin section and to provide either an annular space around the core, or vent holes through it. The objections to vent holes are that they must necessarily be of small diameter, and a number of small holes present a greater resistance to the passage of air than the equivalent cross-section in an annular passage; and that they easily become clogged if the motor is not working in a clean atmosphere.

If a machine is required only as a single-phase motor, it is advantageous to use slots of uneven sizes (Fig. 2) and, if useful, the outside of the laminations may depart from the circular form. This, however, is usually only done in the case of repulsion-start motors. The stator laminations of squirrel-cage motors are generally made symmetrical so that they may be wound for polyphase operation.

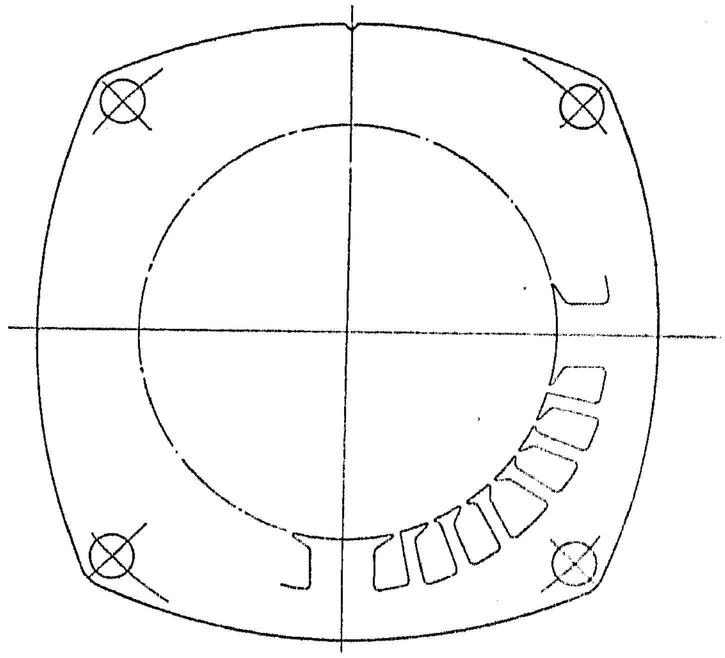

Fig. 2

(4) STATOR SLOTS

It is recommended that the bottom of stator slots should be semicircular (Fig. 3). This reduces the cost of tool-making and gives a definite improvement in the flow of flux into the tooth. A square end is bad from these points of view, while it is found that the extra space provided in the corners cannot effectively be utilized. Also, a slot cell which is shaped to fit in a square-ended slot is liable to split along the sharp bend, and the spaces which are left in the corners are bad from the heat-transmission aspect.

The top of the slot, however, should be formed by sloping projections on the teeth (Fig. 3). It is found that the slot cell holds better during winding, and the closing of the slot after winding is easier with this shape than with a semicircular shape. An angle of 27° gives good proportions, and is convenient in calculation, since tan 27° is approximately 0·5, so that the dimension d_2 (Fig. 3) is quickly arrived at from the dimension w_2.

The teeth should be made not quite parallel. It is easily seen that there is no case for parallel-sided slots in the class of machines under discussion, as bar windings are out of the question. Since, however, a small proportion of the flux is lost in its passage through the teeth, it is reasonable to make them depart from parallelism by this amount.

It is recommended that on very small machines the tooth width should decrease by about 7½ % while for larger machines it should decrease by about 5 %. In general, this factor should be used to round off calculated slot dimensions rather than regarded as a rigid requirement. The slot opening should not be made less than about 0·075 in. unless absolutely necessary, since winding difficulties arise if it is smaller than this. Subject to this limitation, the opening should be about 20 % to 25 % of the slot pitch.

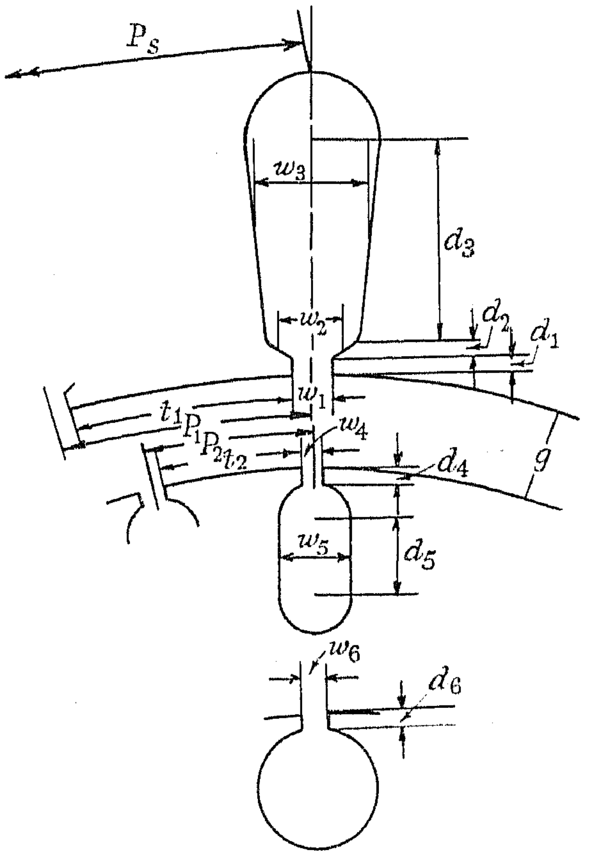

Fig. 3

$$t = \frac{t_1 + t_2}{2}$$

The thickness of the tip at the opening (Fig. 3, d_1) should be about 0·04 in. to 0·06 in. If the bore is to be ground, or otherwise finished to size, allowance must, of course, be made on this dimension accordingly. It is generally found that internal machining of the stator bore is not necessary if the construction is good, and should be avoided since the short-circuiting of laminations, which is liable to occur, more than offsets any gain from the finish.

A popular thickness for laminations is 0·018 in., and unless very high efficiency is aimed at, this is quite thin enough. It is a good plan to place two laminations $\frac{1}{16}$ in. thick at either end of the core to help to keep it tight along the teeth. These thick laminations may, with advantage, be dished before being placed in position. The grade of iron used for stator laminations should be chosen for its high permeability rather than its low iron loss. Any gain in iron loss due to the employment of low-loss iron is usually more than offset by an increase in the copper loss due to the magnetizing current.

Considerable advantage is to be gained by annealing laminations after stamping. During the stamping process the iron appears to become work-hardened around the slots, and this hardening affects the permeability of the iron. This is obviously particularly marked in a case where the teeth are very narrow, or where the flux density is high. Annealing also seems to help in reducing " noise," probably because the core packs tighter.

The use of rivets to hold the laminations together is sometimes condemned, but the author is of the opinion that losses due to steel rivets placed near the outer periphery are negligible. What is more important is that these rivets should be adequate to hold the laminations in a really tight pack. The section of the rivets should not be less than that required to sustain the pressure which is necessary to compress the pack during manufacture.

(5) COPPER ROTOR WINDINGS

In dealing with small rotors, particularly if a large number of bars is employed (i.e. between 30 and 50), it will be found that round bars are undesirable, owing to the narrow " tooth " which results. A rectangular bar with rounded ends (Fig. 3) is recommended. The depth of the bar should be kept a minimum. A good ratio of depth to width is usually between 2½ and 3 to 1. The actual proportions should be chosen so that the real flux density in the teeth at points situated two-thirds of the distance from the wide end is about equal to that in the stator teeth.

The shape of the slot should be similar to that of the bar. The clearance allowed round the bar is very important. It is now common practice to make the copper bars serve as rivets to hold the laminations tight, and if the bars are not a correct fit in the slot, great difficulty is experienced in manufacture, especially if the slots are skewed. A clearance which has been found satisfactory in the case where the skew is equal to twice the slot pitch is 12½ % on the width of the bar and 10 % on the depth. It must be appreciated that this clearance depends very largely on the actual method used for riveting the bars up, and these clearances cannot, therefore, be regarded as definite.

It is quite a common practice to employ no slot opening on the rotor. In the author's opinion, the advantages of this practice are questionable, while the disadvantages are definite and important. First, the " zigzag " leakage is increased to an extent practically impossible to estimate. The iron loss due to the tooth pulsations is similarly increased. The most serious objection, however, is the fact that a constant value for the rotor slot leakage cannot be relied on. A slight difference in the position of the slot in successive batches of stampings, or a variation in the amount of metal removed from the rotor periphery to obtain the air-gap, produces marked differences in test results. A common source of trouble is due to eccentricity as between the blank and the piercing of the slots, so that on one side of the rotor the bridges are thicker than on the other. This last point is liable to accentuate magnetic noise. It is recommended, therefore, that an opening of 0·025 to 0·035 in. with a lip thickness of 0·015 to 0·025 in. be employed. These dimensions are, of course, finished sizes.

For end rings a common and convenient practice is to use copper discs punched out like the steel stampings. A suitable thickness is about 0·063 in. If a greater thickness is required more than one disc should be employed. Thicker discs are more difficult to punch, and cause trouble in the assembly of skewed slots. Satisfactory contact is achieved if the bars and rings are tinned before riveting and dipped in solder afterwards.

(6) ALUMINIUM ROTOR WINDINGS

The ratios of gap diameter to outside diameter given in Fig. 1 apply to rotors having copper windings. Of recent years the use of cast aluminium for squirrel-cage rotors has been extended to f.h.p. machines. While, in a case where plant has been installed to cast large rotors, it may be economical also to cast small ones, the installation of plant purely for the latter is a matter for very careful investigation.

The specific resistance of pure aluminium is given as 1·68 times that of copper. Although it is quite possible to regulate the " impurities " in the metal used for casting, and so to maintain the specific resistance within reasonable limits, the actual figure is invariably higher than that for pure aluminium. Depending on the casting method and the proportions of the squirrel cage, other constituents, such as silica, may be deliberately added to improve the flow of the metal, and thus obtain homogeneous and consistent results. Any such additions, of course, increase the specific resistance. Great care must be taken to control the casting process once production has commenced, otherwise serious troubles, often difficult to diagnose and remedy, are experienced.

The possibility of extensive standardization is also an important factor. In a plant where large numbers of similar machines are manufactured, and the construction of odd machines for special applications is avoided, the case for the cast rotor is much stronger than in a plant which undertakes the production of a large variety of types.

Unless all the practical problems involved are fully considered, and the cost of surmounting them accurately estimated, quite unjustifiable conclusions may be drawn regarding the saving to be achieved by the use of cast rotors in small motors. The question of cast-aluminium rotors versus copper rotors is, therefore, essentially one of manufacturing interest. From the technical aspect the advantage is almost entirely with the copper rotor.

Since the slots for cast bars must be larger, they must either be deeper than the slots for the equivalent copper bars, or the rotor diameter must be increased. To a certain extent this difficulty may be modified by the use of pear-shaped slots giving parallel teeth. If the slots are made very deep the " harmonics " in the speed/torque curve are accentuated, but to some extent this may be offset by the greater ease with which the slots may be skewed. Increasing the rotor diameter necessitates either increasing the outside dimensions, which is undesirable for many reasons, or working at higher flux densities and with tighter and more complicated stator windings. Higher densities have an adverse effect on overload-capacity and other performance figures, while tighter windings may involve not only increased winding cost but increased cost of copper.

A point not to be lost sight of is that if the amount of copper in the coils is increased, it is usually necessary also to increase the length of mean turn, so that the amount of copper in the end winding increases more than in the same proportion as the copper in the slot. Finally, copper rotors can be made without difficulty to show extreme consistency in test results, and while it is not disputed that consistent results can also be obtained with cast-aluminium rotors, not only are the practical difficulties greater but data obtained on one design are less applicable to another.

(7) SLOT NUMBERS

It is well known to designers of electrical machines that the numbers of slots on the stationary and revolving elements are important, but that the ratio between the two is even more important. From the point of view of performance and quiet running, it is better to use a large number of slots, but of course there are practical limits to this. For example, a motor having a gap diameter of 3½ in. might have, for 4 poles, 24, 36, or 48 slots. Intermediate numbers may be used, but, if this is done, the winding becomes less simple. It will be found that 36 slots is about the practical limit for such a size, because if more are used the minimum practical thickness of slot insulation becomes too large a proportion of the slot width, and the cost of winding (being to a large extent a function of the number of coils) becomes prohibitive. For such a size, however, 24 slots is quite common, and although with simple windings 36 slots gives a quieter machine, much of this disadvantage may be overcome if the winding in 24 slots is distributed as described later in the paper. Since the stator winding generally represents the greatest single item of cost in the machine, a careful consideration of the various alternatives is well repaid.

With regard to the number of rotor slots, here again the rule should be to employ as many as practical and economic considerations will allow. The limit for design reasons may be taken as when the depth of the bar exceeds 4 times the width, although for other reasons this limit may be too high.

(8) SLOT RATIOS

On the subject of slot ratios in induction motors, much has been said and written. It was held for a long time that the number of rotor slots should be a prime number, or that the number must be odd. In actual practice, it is found that neither of these conditions is necessary. A slot which gives a quiet machine, both during starting and while running, will also be found to give a good speed/torque characteristic. Skewing is, however, advisable, even with a good slot ratio. It may further be taken that a ratio which gives good results on single-phase will also give good results on 3-phase, but the reverse is not always true. It is advisable, therefore, to choose a ratio which gives satisfaction when the machine is wound for single-phase operation.

The author has found that the following method, which is largely empirical, gives reliable results. The fundamental and "harmonic" stator poles should first be written down, thus: $2p$, $3 \times 2p$, $5 \times 2p$, $7 \times 2p$, $9 \times 2p$, etc. The slot ratio is a good one if the two numbers N_1, N_2, given by the following formula, are equal to two of the above numbers, excluding the first. Thus

$$N_1 \text{ or } N_2 = 2(p \pm \delta) \quad . \quad . \quad . \quad . \quad (3)$$

where δ is the difference between the number of slots on the stator and the number on the rotor.

It is immaterial whether N_1 and N_2 are positive or negative, and whether the stator or the rotor has the larger number of slots. Further, it may be taken that the larger the numbers given by this formula, the more satisfactory is the slot ratio. It will be noted that this gives a series of possible ratios for one number of stator poles. It has been already stated that it is usual on f.h.p. motors to use the same number of laminations for more than one number of poles. This applies also to rotor laminations. It is therefore necessary to examine any proposed ratio for all numbers of poles for which it will be used. Where a compromise is necessary, it may be taken that the nearer the numbers N_1 and N_2 are to two of the "harmonics" the better, but that it is more necessary to achieve coincidence when the number of stator poles is small than when it is large.

For example, considering a stator with 36 slots, to be wound for 4 poles, the fundamental and "harmonic" stator poles are

4, 12, 20, 28, 36, etc.

Choosing 44 rotor slots,

$$N_1 \text{ and } N_2 = 2(2 \pm 8) = -12 \text{ or } +20 \quad . \quad . \quad (4)$$

Choosing 48 rotor slots,

$$N_1 \text{ and } N_2 = 2(2 \pm 12) = -20 \text{ or } +28 \quad . \quad (5)$$

Either of the above rotors will therefore be satisfactory. If now the machine is to be wound for 6 poles, the fundamental and "harmonic" stator poles are

6, 18, 30, 42, 54, etc.

and 44 rotor slots gives

$$N_1 \text{ and } N_2 = 2(3 \pm 8) = -10 \text{ or } +22 \quad . \quad . \quad (6)$$

but 48 rotor slots gives

$$N_1 \text{ and } N_2 = 2(3 \pm 12) = -18 \text{ or } +30 \quad . \quad (7)$$

It is therefore better to use 48 slots, so that the machine will be equally suitable for winding for either 4 or 6 poles.

(9) STATOR WINDINGS

For single-phase machines the concentric type of winding is generally used. For 3-phase machines a lap winding, either single or double, is common, but a winding which may be described as "concentric-lap" is useful, since it gives a rather smaller end-winding length than a lap winding. In this winding the coils for one phase and one pole are formed in a concentric group, but one side only of each coil is placed in its slot, and the first sides of the next group are placed in their slots before the second sides of the first group. This winding keeps down the end-winding projection, but occupies rather more space in the radial direction as compared with a lap winding. In the case of a 2-pole stator a lap winding is preferable, since chording can be used to advantage.

A valuable contribution to silent running in single-phase motors is the distribution of the stator winding in order to approximate to a sinusoidal flux space distribution. In a simple single-phase concentric winding, the main winding usually occupies two-thirds of the slots, and the starting winding the remaining one-third, and all coils of the same winding have the same number of turns. To approximate to a sinusoidal distribution, the main winding must be spread over 80 % to 85 % of the total number of slots, the coils do not all have the same number of turns, and certain slots are shared by the two windings. For a given number of stator slots, this type of winding is more expensive in labour than the simple type. The effect on silent running, however, is important, and, for a given degree of silence, such a winding allows a smaller number of stator slots to be used, so that in this way the winding cost may be brought back to normal.

By way of example, it is found that a 24-slot 4-pole stator with a distributed winding will probably give as quiet a machine as a 36-slot stator with a simple winding. A good practice, therefore, is to employ 36 slots with a simple winding for ordinary use, and a distributed winding in the same stator to give a "super-silent" machine. Since some of the slots are shared by both windings, care must be taken to see that the two windings together with the insulation required between them are not too much for the size of the slot.

Table 1

Coil	Tooth angle (θ) (degrees)	Sin θ	Difference	Conductors
5	7·5	0·13	0·13	14·1
4	22·5	0·383	0·253	27·5
3	37·5	0·61	0·227	24·7
2	52·5	0·79	0·18	19·6
1	67·5	0·92	0·13	14·1
				100 %

(10) SINUSOIDAL DISTRIBUTION

Referring to Fig. 4, it will be seen that in order to approximate to a sinusoidal distribution the number of conductors in each slot should be chosen so that they build up the flux in the adjacent tooth to the point on a sine wave which intersects the vertical line through the tooth centre. That is to say, the number of conductors in the slot should be based on the angular position of the adjacent tooth and not on the angular position of the slot itself. The outer coil should make a full pole pitch and thus occupy the same slots as the outer coils of the poles on either side of it. The required number of turns may be established by the following method, which is best explained by reference to an example.

Fig. 4 shows diagrammatically the winding for one group (i.e. one pole) of a single-phase 4-pole motor, having 48 stator slots. This amounts to 12 slots per pole, of which 10 are occupied to some extent by the running winding. The angular displacement of each tooth towards the centre of the pole is marked, and entered in col. 2 of Table 1. The corresponding sine is entered in col. 3, and in col. 4 are entered successive differences. The total number of conductors having been established (see later), it is entered in the space at the bottom of col. 5, and the numbers of conductors in each coil are then calculated by proportion to the corresponding difference in col. 4.

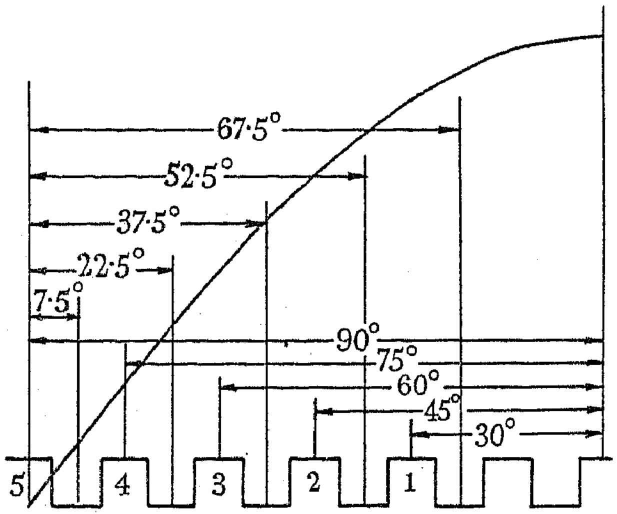

Fig. 4.—Winding diagram for one pole of single-phase 4-pole motor having 48 stator slots.

(11) DISTRIBUTION FACTOR AND CHORD FACTOR

Unless the winding is concentrated in a single coil per pole, a distribution factor for use in calculating the flux must be established to allow for the distribution of the conductors over the pole face. Referring again to Fig. 4, it will be seen that each coil is effective in creating flux through the pole according to the proportion of the pole which it embraces. That is, it is effective in proportion to the angular displacement (from the centre of the pole) of the slot in which it lies. In the case which is taken to illustrate sinusoidal distribution it is possible to calculate the distribution factor as shown in Table 2.

Table 2

Coil	θ_d (degrees)	Sin θ	Conductors	Effective conductors
1	30	0·5	14·1	7·05
2	45	0·707	27·5	19·45
3	60	0·866	24·7	21·4
4	75	0·966	19·6	18·95
5	90	1·000	14·1	14·1
			100 %	80·95

The distribution factor in this case is therefore $K_d = 0{\cdot}81$. This factor has been established for a number of typical cases and is given in Table 3.

The problem of the squirrel-cage motor is a special case of the above. When the machine is wound as a single-phase motor all the conductors are active with respect to the running winding. It is then a case of

Table 3

SINGLE-PHASE CONCENTRIC WINDINGS

Stator slots	Stator poles	Phase	Slots per phase	Coil pitch	Turns per coil	K_d
24	4	Run	16	1–6 2–5	1 1	0·836
		Start	8	4–9	1	0·966
24	4	Run	18	1–7 2–6 3–5	1 2 1	0·808
		Start	6	4–10 5–9	1 1	0·933
36	4	Run	24	1–9 2–8 3–7	1 1 1	0·831
		Start	12	5–14 6–13	1 1	0·97
36	4	Run	24	1–10 2–9 3–8 4–7	1 2 2 1	0·819
		Start	12	6–14 7–13	1 1	0·925
48	4	Run	32	1–12 2–11 3–10 4–9	1 1 1 1	0·829
		Start	16	7–18 8–17	1 1	0·957
48	4	Run	32	1–13 2–12 3–11 4–10 5–9	1 2 2 2 1	0·822
		Start	16	7–19 8–18 9–17	1 1 1	0·944

conductors spread over the whole pole-face. A calculation by the above method shows that for the usual number of rotor bars the distribution factor may be taken as 0·64. When the stator is wound for 3-phase operation the rotor represents the case of a winding distributed over one-third of the pole face, and the distribution factor is then 0·96. In the case of a lap winding a chording factor must be employed. If the pole pitch is a slots and the actual pitch is b slots then the chording angle is given by

$$\theta_c = \left(\frac{a-b}{a}\right) \times 180^\circ \quad . \quad . \quad . \quad . \quad (8)$$

The chording factor is given by

$$K_c = \cos\left(90^\circ \times \frac{a-b}{a}\right) \quad . \quad . \quad . \quad (9)$$

(12) WINDING FACTOR

Now that the use of enamelled wire is so common, accurate calculation of the number of conductors which can be wound in a slot is of even greater importance than before. The secret of successful mass production of stators wound with this wire lies in the specification of the correct number of conductors per slot. The troubles likely to be experienced if the winding is too tight are easily imagined, but what is often overlooked is that a winding which is too slack will also give trouble due to the movement of the wires after winding. When the slots are shaped as recommended in Fig. 3 and the slot opening is closed by an inverted trough of leatheroid, it will be found that a satisfactory winding factor is 70 %.

The winding factor is employed as follows: The net area of the slot is found by taking the dimensions of the slot, less the thickness of the slot insulation. In this connection it should be noted that when the slot insulation is built up of two or more separate thicknesses of material, the resultant thickness must be taken as the sum of the constituent thicknesses plus 15 % for each additional thickness over one. For instance, using 0·01-in. leatheroid and 0·007-in. empire cloth, the total thickness should be taken as 0·0195 in. The winding in the slot is proportional to d^2z_1, where d is the diameter over the wire insulation and z_1 is the number of conductors per slot. The number of conductors which can be put in the slot is then given by

$$d^2z_1 = (\text{Net area of slot}) \times 0\cdot70 \quad . \quad . \quad (10)$$

(13) END-WINDING LENGTH AND PROJECTION

A reliable method of calculating the length of mean conductor, which, of course, means a reliable method of calculating the mean length of the end winding, is very useful. The well-known methods, whereby the lengths of formed coils are established, are inapplicable to small wire-wound stators. The following method yields, first, the projection P_e of the overhang (Fig. 5), which is an extremely important figure now that there is a tendency to keep down dimensions to a minimum; and, secondly, the length of the end winding. From the latter follows the length of mean conductors by adding the core length.

It is useful to check existing designs in order to cut down waste. It is probable that in most winding shops the development of formers is left to the foreman in charge, with the result that formers which are made too small are corrected, but those which are made too large are left alone unless complaints are received from the assembly department on account of excessive projection of the end winding.

In a concentric winding the projection is proportioned to the amount of copper in the slot and the number of coils per group. It also depends on the number of poles for which the stator is wound. The projection is given by the expression

$$2\cdot1\sqrt{[p \times (\text{coils per group}) \times d^2z_1]} \quad . \quad (11)$$

It may be taken that windings can economically be made to conform to this formula except in the case where very heavy wire is used for low voltage. The figure given by this formula is exclusive of any tape or other insulation wound round the end winding, and of such items as connectors.

The shape of the end portion of a coil in a concentric winding is between an arc A (Fig. 5) and the rectangular shape B. The true length l_e may therefore be taken as the length B multiplied by a constant c less than unity. Thus

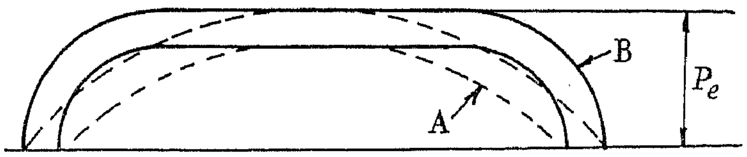

Fig. 5

$$l_e = c\left[\pi \times \frac{P_e}{2} + (P_s - P_e)\right] \quad . \quad . \quad (12)$$

where P_s is the pitch of the mean coil taken on the circle touching the bottom of the slots (Fig. 3).

In practice, it is found that the total length of a coil has an influence on the ease of winding it into the slots. In the case of the two machines, identical except for the length of core, it is found that on the longer core-length the end winding may be shortened slightly without adding to the difficulty of winding.

The above expression (12) may therefore be modified by the factor

$$1 + 0\cdot07\,\frac{\text{Rotor diameter}}{\text{Core length}} \quad . \quad . \quad . \quad (13)$$

The end-winding length (single-phase) is then given by

$$l_e' = 0\cdot90\left[1 + 0\cdot7\,\frac{\text{Rotor diam.}}{\text{Core length}}\right]\left[\pi \times \frac{P_e}{2} + (P_s - P_e)\right] \quad . \quad . \quad (14)$$

In the case of 3-phase stators employing the "concentric-lap" winding, the expression is

$$l_e''' = 0\cdot95\left[1 + 0\cdot07\,\frac{\text{Rotor diam.}}{\text{Core length}}\right]\left[\pi \times \frac{P_e}{2} + (P_s - P_e)\right] \quad . \quad . \quad (15)$$

(14) LEAKAGE REACTANCE

The calculation of the leakage flux is dealt with in many textbooks,* and from the usual method adopted for slot leakage the following formula for the round-ended slot is derived:—

$$1 \cdot 25\left(0 \cdot 637 + \frac{d_3}{3w_3} + \frac{d_2}{w_2} + \frac{d_1}{w_1}\right) = \lambda_s \quad . \quad (16)$$

where the symbols have the meanings indicated in Fig. 3. Similarly, the rotor slot leakage for the round-ended rectangular case is given by

$$1 \cdot 25\left(1 \cdot 274 + \frac{d_5}{3w_5} + \frac{d_4}{w_4}\right) = \lambda_r \quad . \quad . \quad (17)$$

The rotor leakage is referred to the stator by multiplying by the ratio

$$c_\lambda = \frac{\text{Slots occupied by stator winding}}{\text{Number of rotor slots}} \quad . \quad (18)$$

In the single-phase case two values of c_λ are usually required, one being that corresponding to the number of slots occupied by the running winding, and the other corresponding to the number of slots occupied by the starting winding. In the 3-phase case, all the stator slots are usually occupied by windings. Then

$$\lambda_c = \lambda_r \times c_\lambda \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

In the case of a circular-rotor slot this gives

$$\lambda_r = 1 \cdot 25\left(0 \cdot 637 + \frac{d_6}{w_6}\right) \quad . \quad . \quad . \quad (20)$$

For a closed circular slot, provided the thickness of the bridge is made equal to 18 % of the slot diameter, it may be taken that

$$\lambda_r = 1 \cdot 25 \times 1 \cdot 637 \quad . \quad . \quad . \quad . \quad (21)$$

It must be borne in mind, however, that this equation is only reliable when the bridge is saturated, and is liable to errors due to variations in manufacture, as already discussed.

A formula† which the author has found to give very good results for the zigzag leakage is

$$\lambda_{zz} = \frac{1 \cdot 25}{6} \times \frac{t^4}{P_1^2 P_2 g} \quad . \quad . \quad . \quad . \quad (22)$$

For the end winding in the case of concentric or concentric-lap windings the following has been found satisfactory:—

$$\lambda_e = K_d \frac{(\text{Pole pitch} \times 0 \cdot 5P_e)}{(\text{Active core length})} q_1 \quad . \quad . \quad (23)$$

where the pole pitch is taken on the gap diameter and where q_1 is the number of slots per pole and phase in the stator. The total leakage is then

$$\lambda = \lambda_s + \lambda_c + \lambda_{zz} + \lambda_e \quad . \quad . \quad . \quad (24)$$

and the reactance in ohms is

$$x_t = 12 \cdot 5f \frac{(pq_1 z_1)^2 \times (\text{Active core length}) \times 2 \cdot 54 \times \lambda}{pq_1 \times 10^8} \quad (25)$$

where f is the frequency in cycles per sec.

(15) SHORT-CIRCUIT CURRENT

The resistance per phase on short-circuit is given by the stator resistance (r_1) plus the rotor resistance referred to the stator (r_2). It is usual to assume that the respective windings will be at the steady full-load temperature (i.e. generally 50 deg. C. rise). The total impedance is then

$$Z_t = r_t + jx_t = \sqrt{(r_t^2 + x_t^2)} \quad . \quad . \quad . \quad (26)$$

and the power factor is given by

$$\cos \phi = \frac{r_t}{\sqrt{(r_t^2 + x_t^2)}} \quad . \quad . \quad . \quad . \quad (27)$$

These are the "apparent" impedance and power factor.

In the case of a split-phase motor, care should be taken to calculate the impedance of each winding separately. It is not sufficiently accurate to take the reactance of the starting winding as equal to the reactance of the running winding multiplied by the square of the ratio of their respective total conductors. The two windings occupy different proportions of the stator slots, and may not be distributed in the same way.

The value of the short-circuit current calculated in this manner is less than the test value, because the latter includes the magnetizing current. The test value is called the "actual" short-circuit current, while the value given by the above is called the "apparent" short-circuit current. Fig. 6 shows the short-circuit current correction factor, namely

$$C_k = \frac{\text{Apparent short-circuit current}}{\text{Actual short-circuit current}} \quad . \quad (28)$$

for different values of τ ($= Z_t/Z_0$).

Thus, when predetermining the performance of a motor, the actual test figure may be arrived at by using this curve, while, if constants are being established from test data, care must be taken to use this curve to arrive at the "apparent" value before using it to give the impedance and reactance.

It will be noted that separate curves are required for the single-phase and the 3-phase cases. In the 3-phase case, the line current is, of course, $\sqrt{3}$ times the phase current if the stator is mesh-connected, but as it is usual to connect f.h.p. machines in star (in order to reduce the number of conductors per slot) the line current is usually the same as the phase value. The line current taken by the single-phase motor is the vectorial sum of the short-circuit currents in the starting and running windings.

(16) THE MAGNETIC CIRCUIT

The shape of the slots and teeth has already been dealt with in Section (4). The depth of iron behind the stator slots should be so proportioned that the flux density B_{av} in the core is rather less than the density B_{54} in the teeth. As a guide, it may be taken that suitable densities are 13 000 lines per cm^2 for the core and 13 500 lines per cm^2

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* See, for example, M. G. SAY and E. N. PINK: "The Performance and Design of A.C. Machines" (Pitman, 1936), p. 163.

† L. H. A. CARR: *Electrician*, 1921, vol. 87, p. 76.

for the teeth. This, of course, means that more ampere-turns will be required for the core than for the teeth, but it is necessary to keep down the tooth density in order to avoid noise and excessive iron loss. The depth of iron below the rotor slots is usually ample, but it should not be disregarded, since in some designs it may be reduced to danger point by ventilation holes, etc. If holes are required in the stator core for rivets, each should be placed in line with a tooth. Provided the holes are not larger in diameter than the width of the tooth, they may be disregarded. In order to avoid losses due to circulating currents, these rivets should be placed as near as is mechanically sound to the periphery, and the single-phase stator should be wound so that the rivet lies on the pole centre-line.

With the shape of slot recommended, the effective depth of the iron behind the slots may be taken as the minimum plus 20 % of the radius at the bottom of the slot. In calculating the actual sections of the various paths in the magnetic circuit, it is important to allow for the insulation between the laminations. The type of insulating material which is very popular in f.h.p. machines has a china-clay base and is sprayed on to the steel sheets. The adhesion is so good that the sheets may be stamped out after insulating. For laminations 0·018 in. thick (a popular thickness in this class of work), the active core-length may be taken as 90 % of the actual core-length. If, however, the laminations are annealed after stamping, the film of oxide which appears forms an effective insulation and the factor may be taken as 93 %.

(17) THE FLUX CALCULATION

The flux per pole is given by the expression

$$\Phi = \frac{E_p \times 10^8}{2 \cdot 22\, K_d K_c f (2pq_1) z_1} \quad . \quad . \quad . \quad (29)$$

where E_p is the e.m.f. per phase and allows for the stator impedance drop. In the case of f.h.p. machines, the no-load power factor is usually of the order of 0·2 and the full-load power factor of the order of 0·70 to 0·75. Assuming these values, and that $r_1 = x_1$, the error is not very considerable if it is taken that

$$\text{On no load, } E_p = V_p - I_0 r_1 \quad . \quad . \quad (30)$$

$$\text{On full load, } E_p = V_p - I_0 Z_1 \quad . \quad . \quad (31)$$

where V_p is the applied voltage per phase.
Or, alternatively,

$$\text{On full load, } E_p = V_p - \sqrt{2}I_1 r_1 \quad . \quad (32)$$

where in each case the drop is subtracted arithmetically. This allowance for the stator drop represents one of the most important differences between large- and small-machine design. The assumption which is usually made in large-machine design that the magnetizing current is constant, is not justifiable here.

When calculating the general performance figures of a proposed design, the flux must be deduced from the e.m.f. corresponding to the load in question. If, after a winding has been established, it is found that the preliminary assumption of equality of resistance and reactance is appreciably in error, a revised calculation should be made, using the correct value of E_p. An important consideration is that the difference in the e.m.f. between full load and no load generally produces a marked difference in the iron loss. The result is that if the full-load efficiency is calculated by the summation-of-losses (including stray loss) method laid down in B.S.S. No. 269—1927, the result is pessimistic. For this reason it is recommended that f.h.p. motors should be tested against a brake. For example, on a ¼-h.p. 1 400-r.p.m. split-phase motor the difference between the efficiency values established by the two methods might be 2 points.

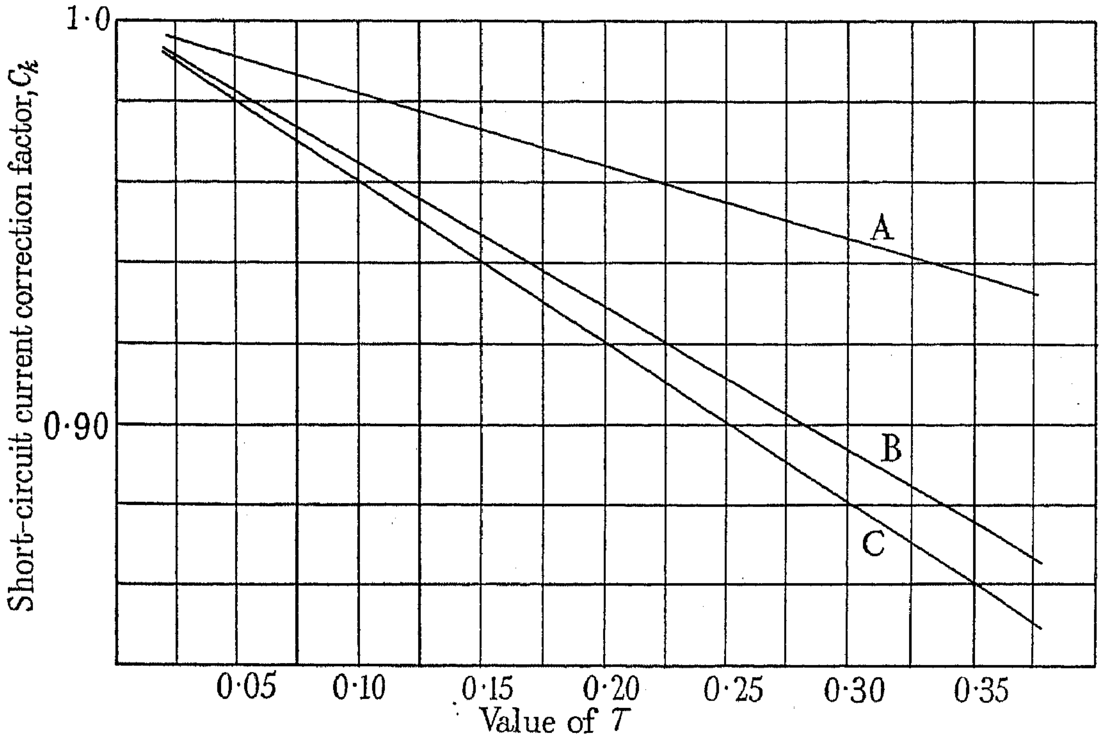

Fig. 6

A. Polyphase motor, $r_2 = r_1$.
B Single-phase motor, $r_2 = r_1$.
C. Single-phase motor, $r_2 = 2r_1$.

(18) THE MAGNETIZING CURRENT

The flux through the core is taken as the value established by equation (29). For the stator and rotor teeth, the value is taken as 1·28 times the core value. This value is, however, reduced by 5 % to $7\frac{1}{2}$ % in its passage through the stator teeth, and by a similar amount in its passage through the rotor teeth.

A magnetization curve is obtainable from the manufacturer of the grade of steel it is proposed to use. When choosing the type of steel, it is very important to consider the iron-loss curve as well as the magnetization curve. It is generally found that a low-loss iron has a low permeability. Careful consideration will show that, generally, permeability is of more consequence than iron loss, since the copper loss due to the magnetizing current may well exceed the iron loss. This is the more likely the smaller the machine or the smaller the power required.

The magnetizing current is found from the total ampere-turns ($\Sigma \bar{A}$) as follows:—

$$\text{Three-phase magnetizing current} = \frac{\Sigma \bar{A}}{2\cdot 22 K_d K_c q_1 z_1} \qquad (33)$$

Single-phase magnetizing current

$$= \frac{\Sigma \bar{A}}{1\cdot 54 K_d K_c q_1 z_1} \times \frac{2 + 2\sigma}{1 + 2\sigma} \quad . \quad . \quad (34)$$

where σ is the flux loss through the teeth (amounting to 10 % to 15 %).

(19) IRON LOSSES

On the assumption that working dimensions are expressed in inches, it is convenient to calculate the volume of iron in the stator core and teeth in cubic inches, and then to use curves giving the watts loss per cubic inch at the frequency in question. The total iron loss may be taken as

$$P_i = (\text{Core volume}) \times (\text{Loss per cu. in.}) + 3\,(\text{Tooth volume}) \times (\text{Loss per cu. in.}) \quad . \quad (35)$$

In each case the loss per cubic inch must be based on the maximum flux density. This value is then, for the core, the average density used to establish the ampere-turns multiplied by 1·59; and, for the teeth, the B_{54} value used in the magnetization table multiplied by 1·24. As has been stated before, care must be taken, when calculating a load performance, to take the magnetizing current and iron loss at that load. Taking the iron loss at full load, an equivalent current and impedance Z_0 may be established as follows:—

$$\text{On single-phase, } I_i = \frac{P_i}{V} \quad . \quad . \quad . \quad (36)$$

$$\text{On 3-phase, } \quad I_i = \frac{P_i}{\sqrt{3}V} \quad . \quad . \quad (37)$$

An equivalent total " loss " current is then

$$I_0 = \sqrt{(I_i^2 + I_m^2)} \quad . \quad . \quad . \quad . \quad (38)$$

where I_m is the magnetizing current at full load. Then

$$Z_0 = \frac{V_p}{I_0} \quad . \quad . \quad . \quad . \quad . \quad (39)$$

The important operator τ is given by the ratio

$$\tau = \frac{Z_t}{Z_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad (40)$$

If it is desired to predetermine the no-load current, it may be found in the same way, using no-load values of iron loss and magnetizing current.

(20) CORRECTION FACTORS

Table 4 gives, for the single-phase case, the method or formulae recommended for obtaining the various performance data. In the adjoining column the correct formulae are given, except in some cases where the complication is excessive. It will be noted that, in the practical column, correction factors appear. These are arrived at by calculating the correct values by means of the formulae in the second column, using nominal values for the various impedances, and for a series of values of τ. The 3-phase formulae have previously been given in a convenient form by Hoseason,* while the method by which the single-phase formulae are obtained is described in the Appendix.

It is found that, in f.h.p. machines, average values for the " loss " current power factor, and the short-circuit power factor, are

Three-phase $\cos\phi_t = 0\cdot 75$, $\cos\phi_0 = 0\cdot 15$
Single-phase $\cos\phi_t = 0\cdot 75$, $\cos\phi_0 = 0\cdot 20$

These values have been used to establish the various correction factors and the power-factor curves.

Fig. 7 gives the correction factor for maximum horse-power (C_P) and Fig. 8 gives the correction factor for maximum torque (C_T), in the polyphase case. Fig. 9 gives the correction factor for maximum horse-power in the single-phase case; a close degree of accuracy is attained if the maximum-torque correction factor in the single-phase case is taken as the constant value 0·86.

The actual (test) value of the short-circuit power factor is lower than the apparent power factor and is given by

$$\cos\phi_k = \left(\frac{r_t}{z_t} \times C_\phi\right) \quad . \quad . \quad . \quad . \quad (41)$$

Fig. 10 gives the correction factors for both polyphase and single-phase cases.

In calculating the polyphase maximum horse-power and torque for practical design purposes, the usual simplified formulae are used in conjunction with the above correction factors. In the single-phase case, however, the method adopted is that of calculating first the slip at which these maxima occur and then using these slip values in calculating the maximum horse-power and torque. It will be noted that in the polyphase case it is assumed that $r_2 = r_1$, but in the single-phase case the ratio of these two values appears, so that accuracy is possible over a wide variation in this ratio.

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* *Journal I.E.E.*, 1925, vol. 63, p. 280.

Table 4

SINGLE-PHASE INDUCTION MOTOR

	Practical	Theoretical
Primary current at slip s	$\frac{\text{Input watts}}{\text{Applied volts} \times \text{p.f.}} = \frac{P}{V_1 \cos \phi}$	$V_1\sqrt{\left[\frac{(s_0r_m + 2r_2)^2 + (s_0x_m + 2sx_2)^2}{(\gamma - s\beta + s_0\epsilon)^2 + (\chi + s\psi + s_0\omega)^2}\right]}$
Power output at slip s	Input minus losses	$\frac{s_0(1-s)^2V_1^2Z_m^2r_2}{(\gamma - s\beta + s_0\epsilon)^2 + (\chi + s\psi + s_0\omega)^2}$
Torque at slip s	Power $\times \frac{1}{1-s}$	$\frac{s_0(1-s)V_1^2Z_m^2r_2}{(\gamma - s\beta + s_0\epsilon)^2 + (\chi + s\psi + s_0\omega)^2}$
Slip at max. power output, s_P	$\frac{r_2}{2Z_t + r_2}$	
Max. output (horse-power), P_m	$\frac{s_{OP}(1 - s_{OP})V_1^2C_P}{r_2\left(1 + 0{\cdot}68\tau + s_{OP}\frac{r_1}{r_2}\right)^2 \times 746}$	From power/slip curve
Slip at max. torque, s_T	$\frac{r_2}{Z_t + x_t}$	
Max. torque (synchronous watts), T_m ..	$\frac{s_{OT}(1 - s_T)V_1^2 \times 0{\cdot}86}{r_2\left(1 + 0{\cdot}68\tau + s_{OT}\frac{r_1}{r_2}\right)^2}$	From torque/slip curve
Power factor	From curves	$\frac{(s_0r_m + 2r_2)(\gamma - s\beta + s_0\epsilon) + (s_0x_m + 2sx_2)(\chi + s\psi + s_0\omega)}{\sqrt{\left[\left\{(s_0r_m + 2r_2)(\chi - s\beta + s_0\epsilon) + (s_0x_m + 2sx_2)(\chi + s\psi + s_0\omega)\right\}^2 + \left\{(s_0x_m + 2sx_2)(\gamma - s\beta + s_0\epsilon) - (s_0r_m + 2r_2)(\chi + s\psi + s_0\omega)\right\}^2\right]}}$
Actual short-circuit current (I_k)	$V_1/(Z_tC_k)$	
Actual short-circuit power factor ($\cos \phi_k$)	$r_tC\phi/Z_t$	
Starting torque	$2I'_{Rk}K_TI'_{Sk} \sin \theta r_2$	

I'_{Rk} = apparent short-circuit current in running winding; I'_{Sk} = apparent short-circuit current in starting winding; K_T = ratio of transformation between the two windings; s = slip; $n = (1 - s)$ = speed; $s_0 = 1 - n^2$; $Z_1 = r_1 + jx_1$ = primary self-inductive impedance; $Z_2 = r_2 + jx_2$ = secondary self-inductive impedance; $Z_m = r_m + jx_m$ = mutual inductive impedance; $Z_t = r_t + jx_t = Z_1 + Z_2$; $\beta = x_2(x_m + 2x_1)$; $\gamma = r_2(r_m + 2r_1)$; $\epsilon = (r_mr_1 - x_mx_1)$; $\theta = \phi'_{Rk} - \phi'_{Sk}$, where $\cos \phi'_{Rk}$ and $\cos \phi'_{Sk}$ are apparent values; $\chi = r_2(x_m + 2x_1)$; $\psi = x_2(r_m + 2r_1)$; $\omega = (r_mx_1 + x_mr_1)$.

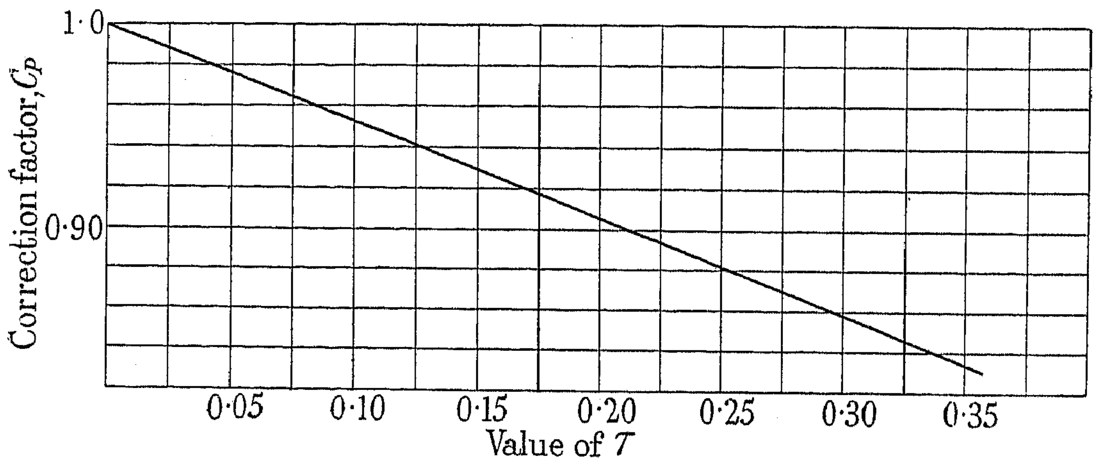


Fig. 7.—Polyphase motor: maximum horse-power correction factor.

$$\text{Maximum horse-power} = \frac{3C_P V_{ph}^2}{2(Z_t + r_t)\,0{\cdot}746}$$

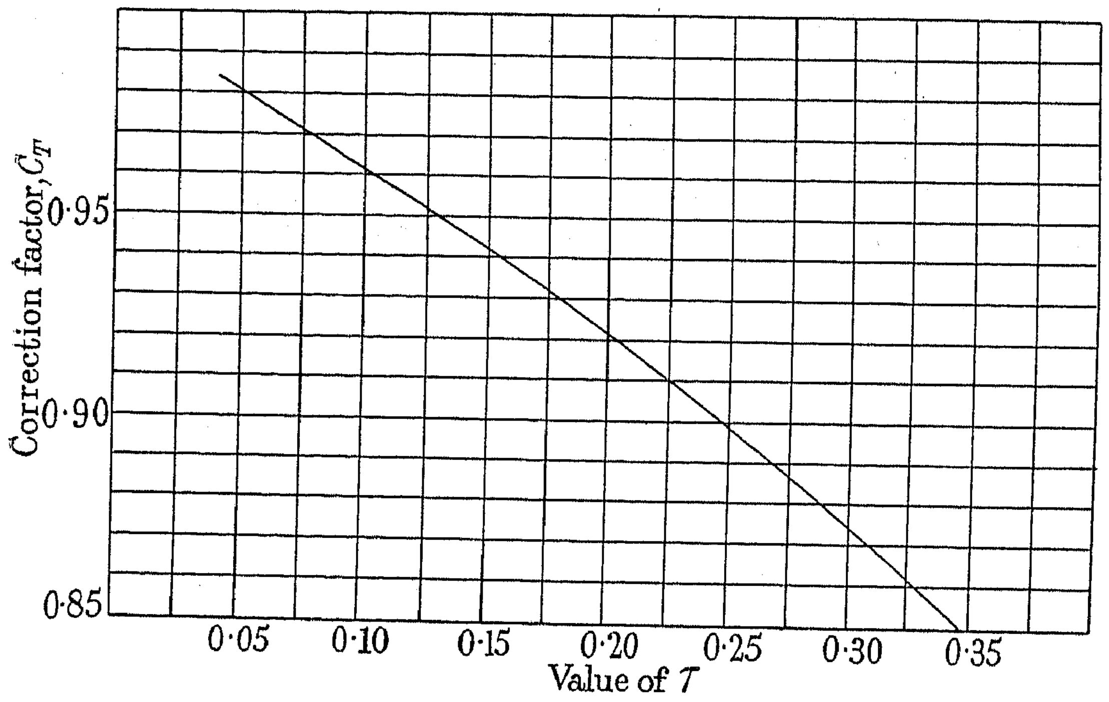


Fig. 8.—Polyphase motor: maximum torque correction factor.

$$\text{Maximum torque} = \frac{3C_T\, V_{ph}^2}{2[r_1 + \sqrt{(r_1^2 + x_t^2)}]}$$

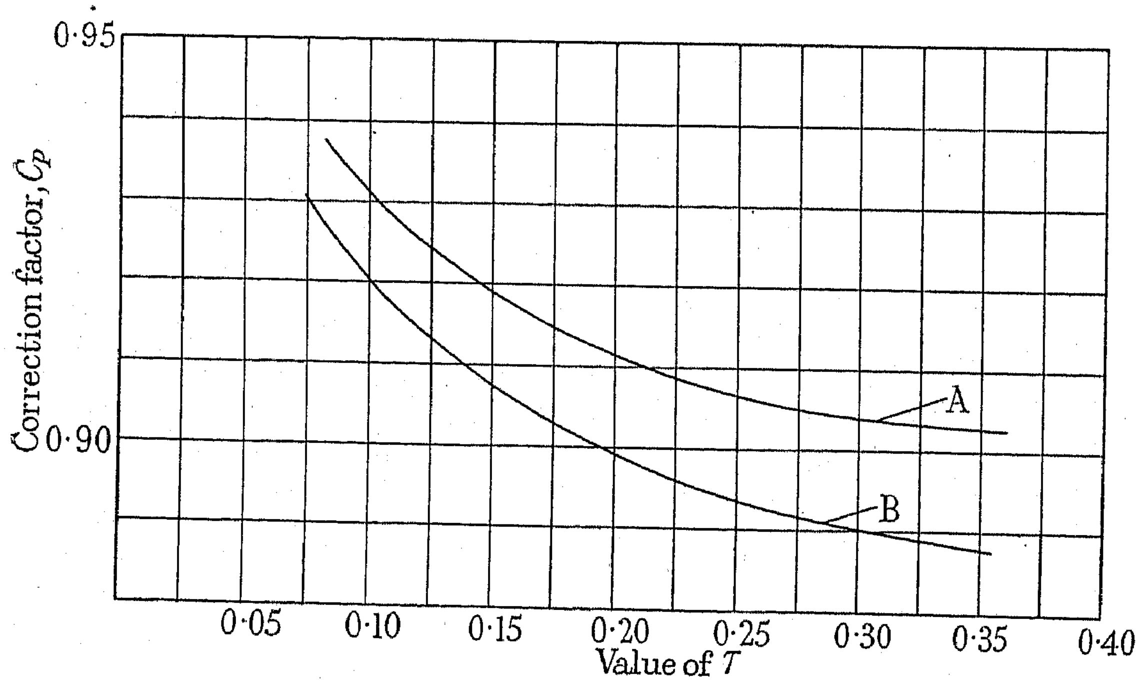


Fig. 9.—Single-phase motor: maximum horse-power correction factor.

A. $r_2 = r_1$.
B. $r_2 = 2r_1$.

(21) STARTING TORQUE OF SPLIT-PHASE MOTOR

The starting torque of the split-phase motor is given by

$$T_k = 2I'_{RK}K_T I'_{SK} \sin\theta \,.\, r_2 \quad . \quad . \quad . \quad (42)$$

where I'_{RK} = apparent short-circuit current in running winding,

I'_{SK} = apparent short-circuit current in starting winding,

θ = angle between these two currents,

r_2 = rotor resistance referred to running winding,

Also K_T = ratio of transformation between the two windings

$$= \frac{K_d \times \text{Conductors in starting winding}}{K'_d \times \text{Conductors in running winding}} \quad . \quad (43)$$

where K_d, K'_d are the distribution factors for the starting and running windings respectively.

The full-load torque in synchronous watts is given by

$$\frac{\text{Horse-power} \times 746}{1 - s} \quad . \quad . \quad . \quad . \quad (44)$$

where s is the slip at full load.

It is usual to equate the two in order to give the starting torque as a percentage of full-load torque.

There is no necessity to complicate the expression by substituting for $\sin\theta$. It is convenient to find the angles corresponding to $\cos\phi'_{RK}$ and $\cos\phi'_{SK}$, deduce θ by subtraction, and then find $\sin\theta$ from trigonometrical tables. The angle θ may be established in a variety of ways, but the majority of practical requirements in f.h.p. motors are met either by adding resistance to the starting winding or by connecting a condenser in series with it. The former is what is generally understood by the term "split-phase" motor, while the latter is called a "capacitor-start" motor.

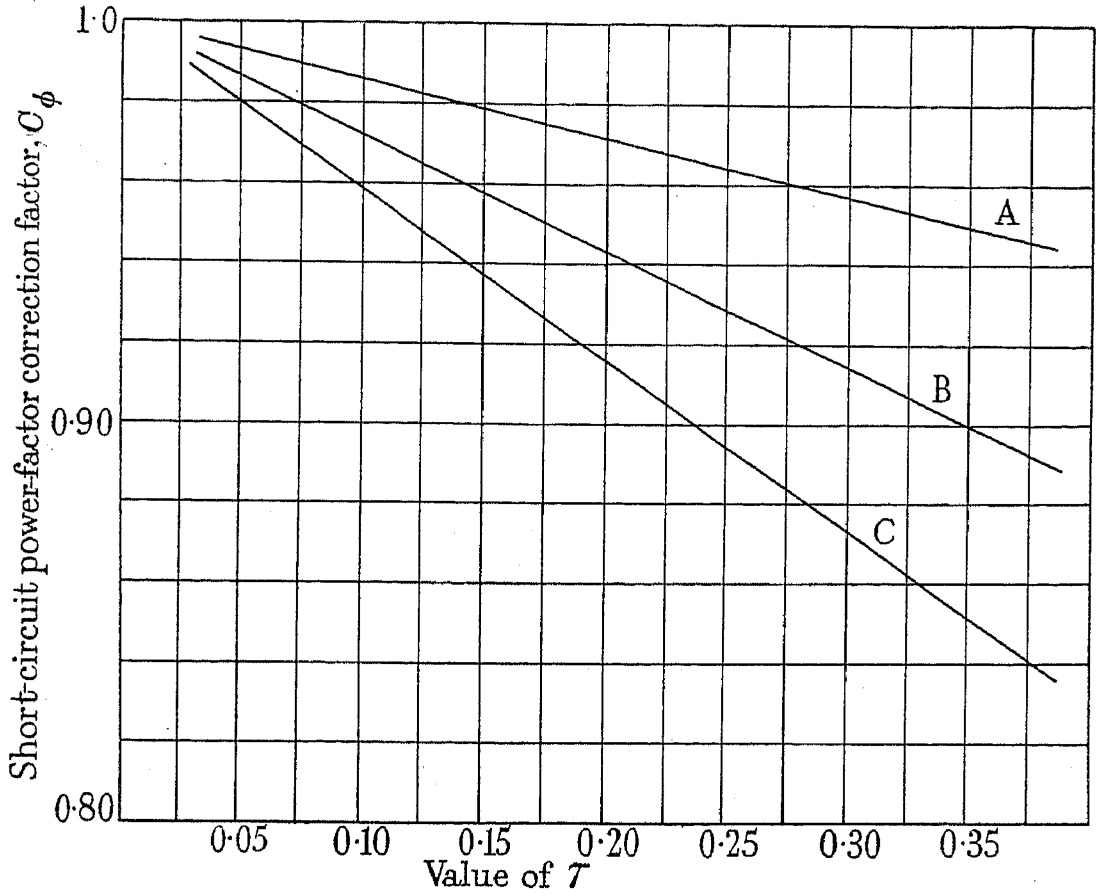


Fig. 10

A. Polyphase motor, $r_2 = r_1$.
B. Single-phase motor, $r_2 = r_1$.
C. Single-phase motor, $r_2 = 2r_1$.

In the split-phase motor, the starting winding usually occupies about half as many slots as the running winding, and has approximately the same number of conductors per coil, so that the total number of conductors in the starting winding is approximately half the number in the running winding. The section of the conductors is reduced to something of the order of 20 % of the section of the running-winding conductors in order to give the required increased resistance using copper wire. Such a winding is of course only suitable provided it is in circuit only a very short time. In practice a centrifugal switch is generally used which cuts out the starting winding as soon as the motor has reached about 80 % of synchronous speed. Under these conditions, the current density at starting may be as high as 60 000 amp. per sq. in. A more robust machine is obtained by using a resistance external to the winding. This may take the form of nichrome wire or tape, wound on mica sheets. This arrangement is, however, becoming obsolete, owing to the extremely low prices ruling for split-phase motors.

The capacitor-start motor is rapidly becoming very popular, mainly because it can be designed to give a very high starting torque for a reasonable starting current. The starting condenser is usually of the electrolytic type which has been developed for this machine. These condensers are very reliable and compact. As a guide, it may be taken that the usual size for a 230-volt 50-cycle

$\frac{1}{4}$-h.p. motor is 30 μF. The condenser, which gives a high starting torque, is too large to be left in circuit when the motor is running. Also, of course, the electrolytic type is only suitable for intermittent duty and must be cut out as soon as the motor is up to speed. In this country it is quite common to use a magnetic switch to open-circuit the starting winding and condenser, but provided the design is good a centrifugal switch is satisfactory and much cheaper. If it is desired to leave a small condenser permanently in circuit in order to obtain a modified 2-phase motor on load, this permanent condenser must be of the paper type. In this case the switch is used to open-circuit the starting condenser only. A large variety of forms of the capacitor-start and run motor has appeared, but at the present time attention is almost entirely confined to the straightforward capacitor-start motor. For drives such as fans where the required starting torque is low, a small single condenser is connected permanently in circuit.

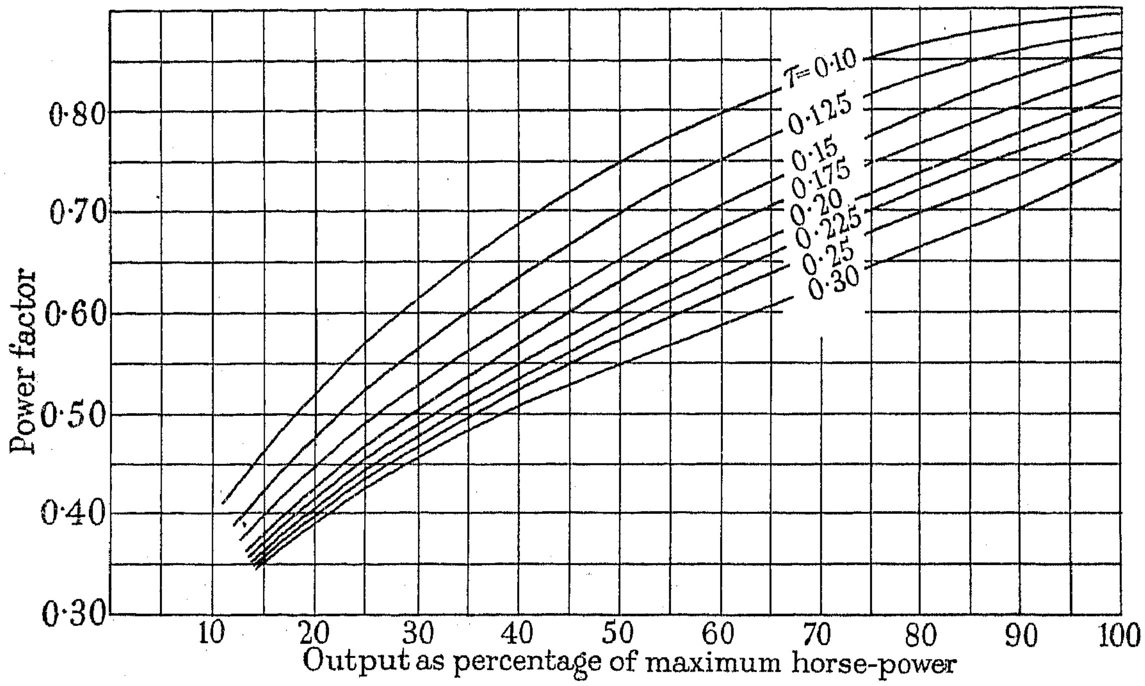


Fig. 11.—Single-phase motor: characteristics based on $\cos\phi_0 = 0\cdot 20$, $\cos\phi_k = 0\cdot 75$, $r_2 = r_1$.

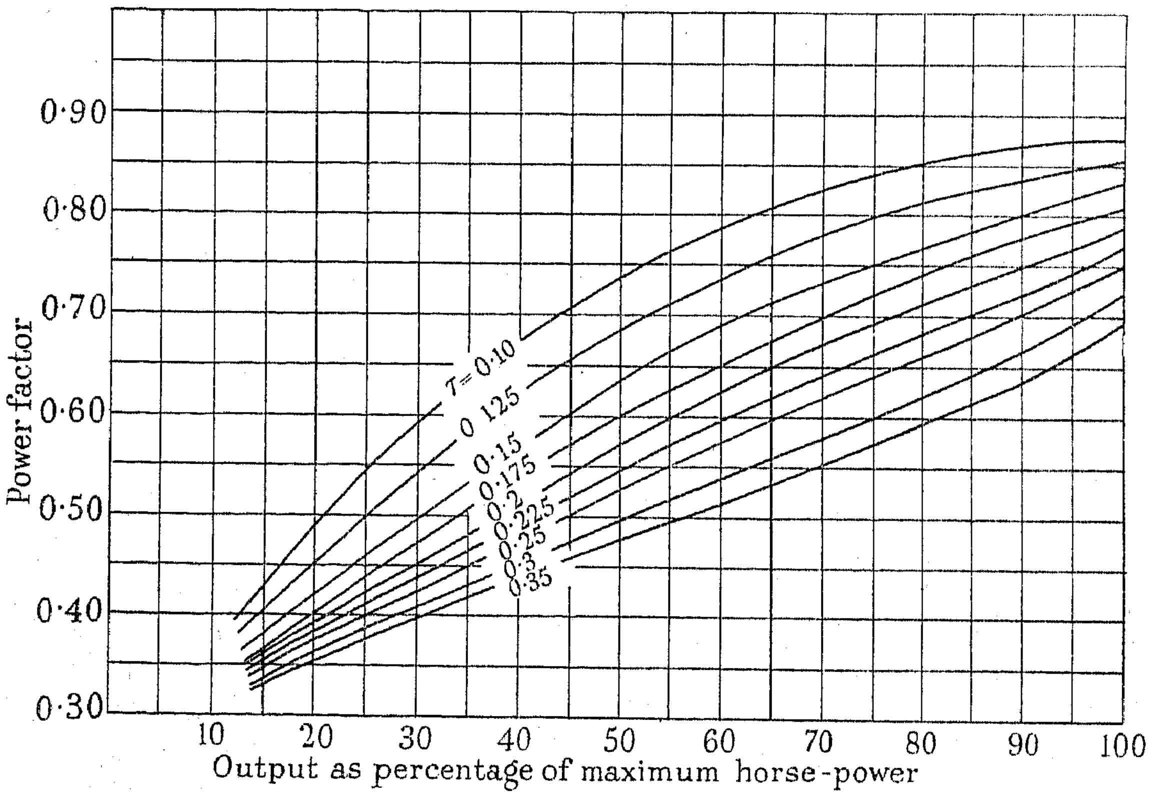


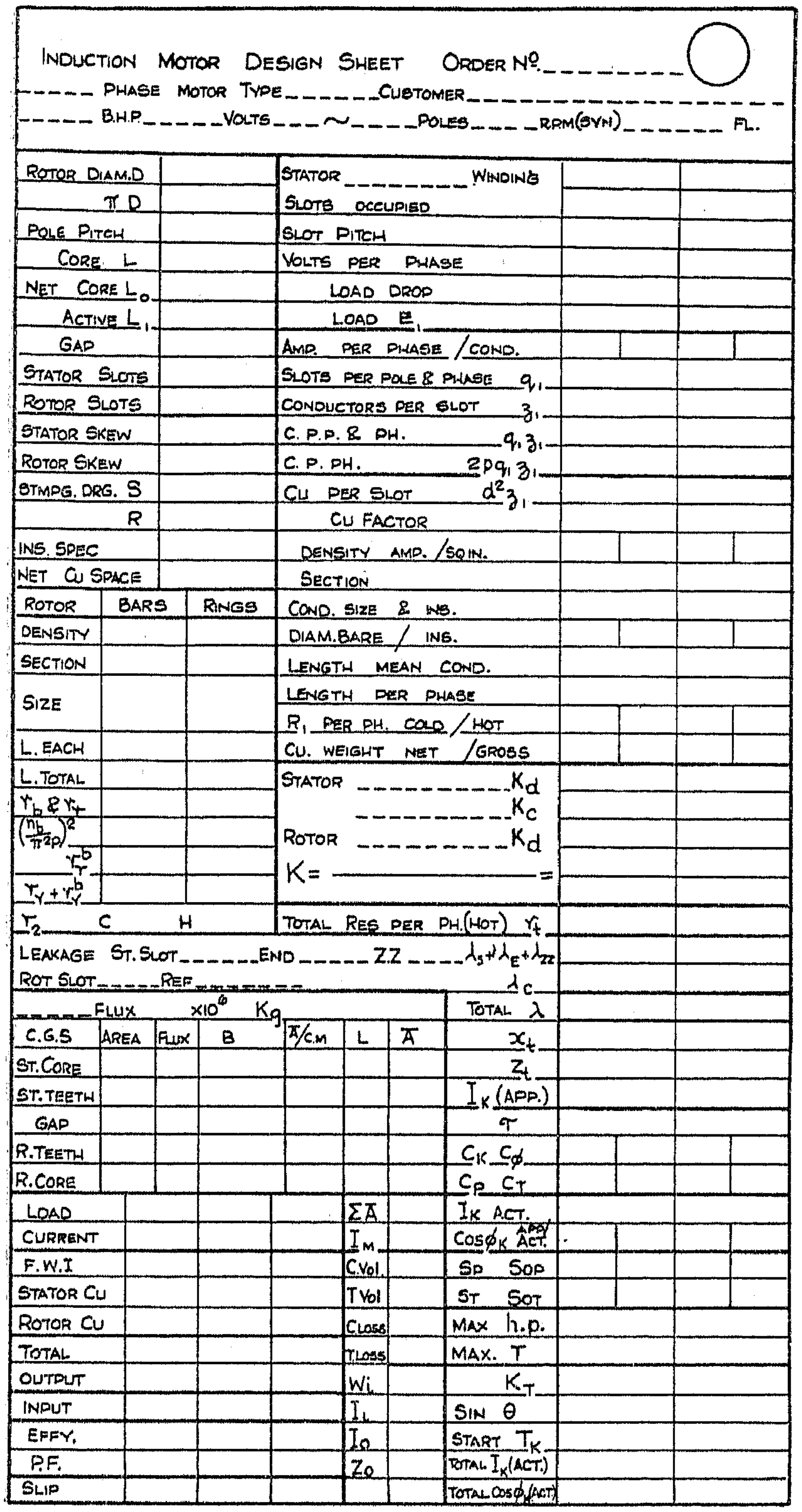
Fig. 12.—Single-phase motor: characteristics based on $\cos\phi_0 = 0\cdot 20$, $\cos\phi_k = 0\cdot 75$, $r_2 = 2r_1$.

The formula given in this paper for the starting torque of the single-phase motor may be used in the capacitor-start case.

(22) CALCULATION OF PERFORMANCE ON LOAD

The efficiency on load may be calculated to a close degree of accuracy, provided the iron loss is based on the actual flux at the load in question, and provided information is available regarding the friction loss in the bearings and the energy required to drive the fan, if one is fitted. Owing to the large variety in fan and bearing designs it

Table 5



Induction Motor Design Sheet Order No.________
_____ Phase Motor Type______Customer________________
_____ B.H.P._____Volts___～____Poles____R.P.M.(Syn)______ F.L.

Rotor Diam. D		Stator ________ Winding		
π D		Slots occupied		
Pole Pitch		Slot Pitch		
Core L		Volts per Phase		
Net Core L_0		Load Drop		
Active L_1		Load E_1		
Gap		Amp. per Phase /Cond.		
Stator Slots		Slots per Pole & Phase q_1		
Rotor Slots		Conductors per Slot z_1		
Stator Skew		C. P.P. & Ph. $q_1 z_1$		
Rotor Skew		C. P. Ph. $2pq_1z_1$		
Stmpg. Drg. S		Cu per Slot $d^2 z_1$		
R		Cu Factor		
Ins. Spec		Density Amp./Sq.in.		
Net Cu Space		Section		

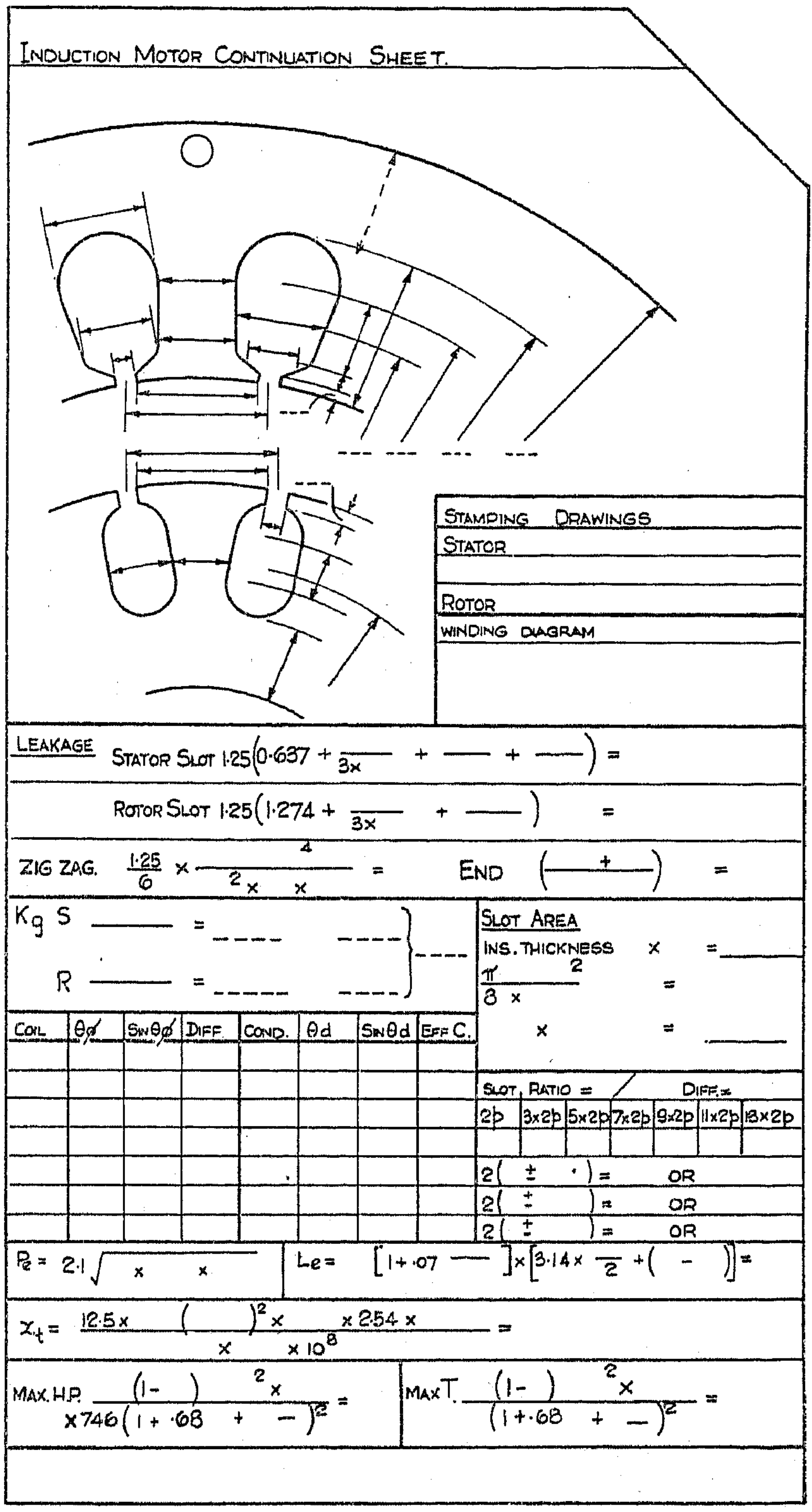
Rotor	Bars	Rings			
Density			Cond. Size & Ins.		
Section			Diam. Bare / Ins.		
Size			Length Mean Cond.		
			Length per Phase		
			R_1 per Ph. Cold / Hot		
L. Each			Cu. Weight Net /Gross		
L. Total			Stator __________ K_d		
r_b & r_r			__________ K_c		
$\left(\frac{n_b}{\pi^2 p}\right)^2$			Rotor __________ K_d		
r_r^b			K = ________ =		
$r_r + r_r^b$					
r_2	C	H	Total Res per Ph. (Hot) r_t		

Leakage St. Slot______End_____Z.Z____ $\lambda_s+\lambda_E+\lambda_{zz}$
Rot Slot_____Ref________ λ_c
_____Flux ×10⁶ K_g Total λ

C.G.S	Area	Flux	B	A/cm	L	A			
							x_t		
St. Core							z_t		
St. Teeth							I_K (App.)		
Gap							τ		
R. Teeth							C_K C_ϕ		
R. Core							C_P C_T		

Load				ΣA		I_K Act.		
Current				I_M		Cos ϕ_K App./Act.		
F.W.I				C.Vol.		S_P S_{OP}		
Stator Cu				T.Vol		S_T S_{OT}		
Rotor Cu				C.Loss		Max h.p.		
Total				T.Loss		Max. T		
Output				Wi		K_T		
Input				I_L		Sin θ		
Effy.				I_0		Start T_K		
P.F.				Z_0		Total I_K (Act.)		
Slip						Total Cos ϕ_K (Act.)		

Table 6



Induction Motor Continuation Sheet.

Stamping Drawings
Stator

Rotor
Winding Diagram

Leakage Stator Slot $1{\cdot}25\left(0{\cdot}637 + \frac{}{3\times} + \frac{}{} + \frac{}{}\right) =$

Rotor Slot $1{\cdot}25\left(1{\cdot}274 + \frac{}{3\times} + \frac{}{}\right) =$

Zig Zag. $\frac{1{\cdot}25}{6} \times \frac{4}{{}^{2}\times \quad \times} =$ End $\left(\frac{+}{}\right) =$

K_g S ______ = ____ ____ } ____
R ______ = _____ ____

Slot Area
Ins. Thickness × = ______
$\frac{\pi}{8\times}{}^{2}$ =
× = ______

Coil	θφ	Sin θφ	Diff	Cond.	θd	Sin θd	Eff C.

Slot Ratio = / Diff. =

2p	3×2p	5×2p	7×2p	9×2p	11×2p	13×2p

2(±) = OR
2(±) = OR
2(±) = OR

$R_e = 2{\cdot}1\sqrt{\ \times\ \times\ }$ $L_e = \left[1 + {\cdot}07\,\frac{}{}\right]\times\left[3{\cdot}14\times\frac{}{2} + (\ -\ )\right] =$

$x_t = \frac{12{\cdot}5\times(\quad)^2\times\quad\times 2{\cdot}54\times}{\times\quad\times 10^8} =$

Max. H.P. $\frac{(1-\ )\ {}^{2}\times}{\times 746\left(1 + {\cdot}68 + \frac{}{}\right)^2} =$ Max T. $\frac{(1-\ )\ {}^{2}\times}{\left(1 + {\cdot}68 + \frac{}{}\right)^2} =$

is difficult to give figures for these items, but, as a guide, it may be taken that for a machine with ball bearings the friction and windage loss at 1 400 r.p.m. should not exceed 7½ % of the full-load output. For a machine with sleeve bearings of good design, this loss should not exceed 10 %.

In the single-phase case, the slip at maximum horse-power is first calculated, and from this the maximum horse-power is obtained. Using the value of τ already determined, the power factor at any load follows from the curves of Figs. 11 or 12, whichever is applicable. In the 3-phase case the maximum horse-power is calculated in the usual manner, and then the power factor follows from the curves given in Fig. 13. The primary current is arrived at by a process of trial and error in the usual manner, since the stator copper loss depends on the current assumed. Incidentally, the calculation of the slip at maximum horse-power in the single-phase case is useful in establishing the speed at which the centrifugal switch should operate.

For ordinary use, and since the designer of f.h.p. machines is generally called on to produce a large number of designs and has very little time to spend on each, the two types of design sheets reproduced in Tables 5 and 6 are recommended. Both sheets are used in the case of an original design, and they then record the complete data for the machine. Obviously, once a number of machines have passed through their tests, it is useful to go back and correct the original design if the average test figures depart materially from it. When, however, a modification of an existing design will meet the case, the first sheet (Table 5) only is often sufficient, or in some cases part only of the second sheet may be used. Once a design has been established, it is usually required for

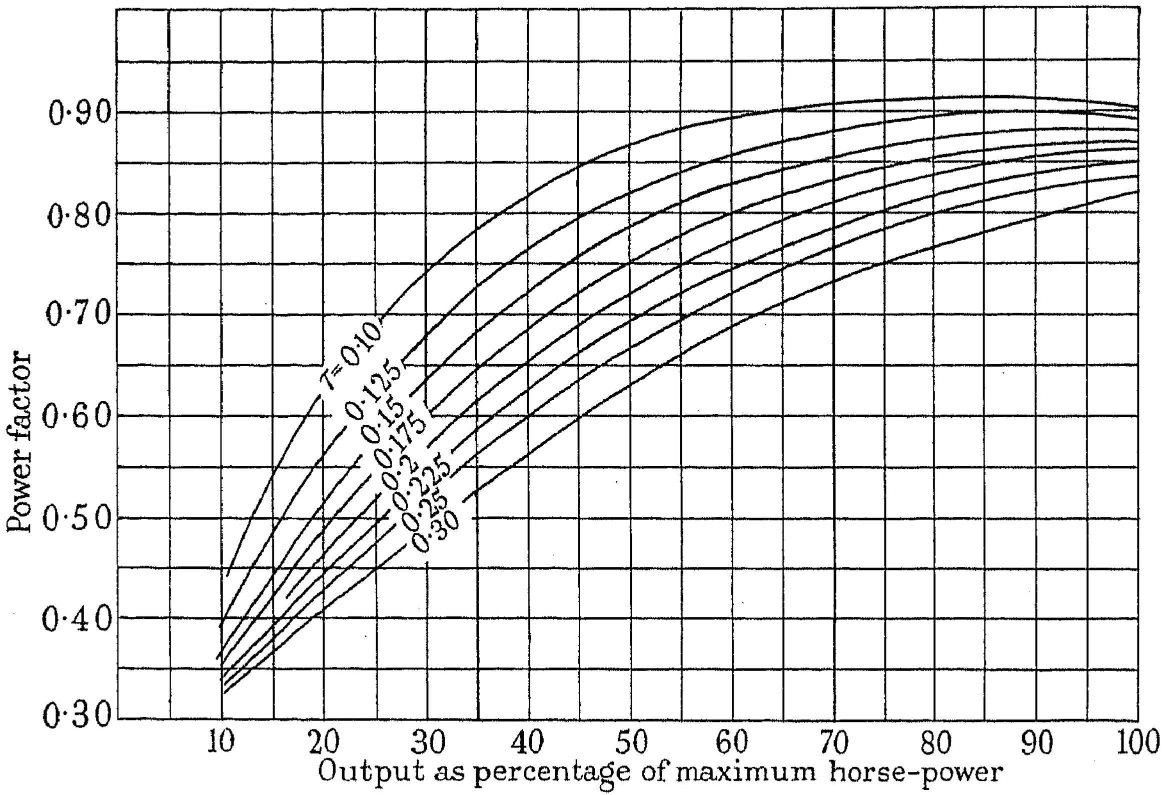


Fig. 13.—Polyphase motor: characteristics based on $\cos\phi_0 = 0\cdot15$, $\cos\phi_k = 0\cdot75$, $r_2 = r_1$.

various voltages and frequencies, in which case it is useful to use simple winding record sheets which are filed with the corresponding complete design sheet. Windings for various voltages and frequencies are quickly established from the formula

$$T_R = T_S \times \frac{V_R}{V_S}\sqrt{\left(\frac{\text{Standard h.p.}}{\text{Required h.p.}} \times \frac{f_S}{f_R}\right)} \qquad (45)$$

where the subscripts R and S stand for " required " and " standard " respectively. It is strongly recommended that the design sheets be used whenever applicable, even though at the time only a few figures can be filled in.

(23) ACKNOWLEDGMENTS

The author is indebted to Mr. D. B. Hoseason, Member, for much helpful advice and criticism, particularly in connection with the calculation of the curves reproduced in Fig. 13, also to Miss D. Smith, Associate Member, for checking various calculations.

Much assistance in checking formulae was derived from test figures supplied by Lancashire Dynamo and Crypto, Ltd.

APPENDIX

Derivation of Single-phase Performance Formulae

The following notation is employed in this Appendix:—

I_1 = primary current;
n = speed = $1 - s$;
$s_0 = 1 - n^2$;
V_1 = applied voltage;
$Z_m = r_m + jx_m$ = mutual inductive impedance;
$Z_1 = r_1 + jx_1$ = primary self-inductive impedance;
$Z_2 = r_2 + jx_2$ = secondary self-inductive impedance;
$Z_t = r_t + jx_t = Z_1 + Z_2$.

It was shown by Steinmetz* that, neglecting quantities of the second order, the primary current is given by

$$I_1 = \frac{V_1[Z_m s_0 + 2Z_2]}{Z_m(Z_1 s_0 + Z_2) + 2Z_1 Z_2}$$

The numerator of this expression, when expanded, becomes

$$\left[V_1(s_0 r_m + 2r_2) + j(s_0 x_m + 2sx_2)\right]$$

The denominator becomes

$$r_2(r_m + 2r_1) + s_0(r_m r_1 - x_m x_1) - sx_2(x_m + 2x_1) \\ + j\left[r_2(x_m + 2x_1) + sx_2(r_m + 2r_1) + s_0(r_m x_1 + x_m r_1)\right]$$

The expression then takes the form

$$I_1 = V_1\frac{(s_0 r_m + 2r_2) + j(s_0 x_m + 2sx_2)}{(\gamma - s\rho + s_0\epsilon) + j(\chi + s\psi + s_0\omega)}$$

where

$$\gamma = r_2(r_m + 2r_1), \qquad \chi = r_2(x_m + 2x_1),$$
$$\rho = x_2(x_m + 2x_1), \qquad \psi = x_2(r_m + 2r_1),$$
$$\epsilon = (r_m r_1 - x_m x_1), \qquad \omega = (r_m x_1 + x_m r_1).$$

When rationalized, the numerator becomes

$$V_1\Big\{\left[(s_0 r_m + 2r_2)(\gamma - s\rho + s_0\epsilon) + (s_0 x_m + sx_2)(\chi + s\psi + s_0\omega)\right] \\ + j\left[(s_0 x_m + sx_2)(\gamma - s\rho + s_0\epsilon) - (s_0 r_m + 2r_2)(\chi + s\psi + s_0\omega)\right]\Big\}$$

The denominator becomes

$$(\gamma - s\rho + s_0\epsilon)^2 + (\chi + s\psi + s_0\omega)^2$$

But V_1 and the denominator are scalar, and therefore the power factor is given by

$$\cos\phi = \frac{x}{\sqrt{(x^2 + y^2)}}$$

---

* "Theory and Calculation of Electrical Apparatus," p. 317.

where

$$x = (s_0 r_m + 2r_2)(\gamma - s\rho + s_0\epsilon) + (s_0 x_m + 2sx_2)(\chi + s\psi + s_0\omega)$$
$$y = (s_0 x_m + 2sx_2)(\gamma - s\rho + s_0\epsilon) - (s_0 r_m + 2r_2)(\chi + s\psi + s_0\omega)$$

The primary current is

$$I_1 = V_1\sqrt{\left[\frac{(s_0 r_m + 2r_2)^2 + (s_0 x_m + 2sx_2)}{(\gamma - s\rho + s_0\epsilon)^2 + (\chi + s\psi + s_0\omega)^2}\right]}$$

Similarly the power output at slip s is

$$P = \frac{s_0(1-s)^2 V_1^2 Z_m^2 r_2}{(\gamma - s\rho + s_0\epsilon)^2 + (\chi + s\psi + s_0\omega)^2}$$

and the torque at slip s is

$$T = \frac{s_0(1-s) V_1^2 Z_m^2 r_2}{(\gamma - s\rho + s_0\epsilon)^2 + (\chi + s\psi + s_0\omega)^2}$$

A simplified expression for the maximum power output, for practical use, is obtained as follows.

The maximum power is given by

$$P_{max.} = \frac{s_{0P}(1-s_P)^2 V_1^2 Z_m^2 r_2}{(\gamma - s_P\rho + s_{0P}\epsilon)^2 + (\chi + s_P\psi + s_{0P}\omega)^2}$$

where s_P and s_{0P} are the values of s and s_0 corresponding to maximum power.

By differentiating the above expression it is shown that

$$s_P = \frac{r_2}{2Z_t + r_2}$$

At maximum power, however, it is possible to neglect $(\gamma - s_P\rho + s_{0P}\epsilon)$ and also $s_P\psi$. In the equation

$$\omega = (r_m x_1 + x_m r_1)$$

the part $r_m x_1$ may also be neglected. The expression for the maximum power output then becomes

$$P_{max.} = \frac{s_{0P}(1-s_P)^2 V_1^2 Z_m^2 r_2}{(r_2 x_m + 2r_2 x_1 + s_{0P} x_m r_1)^2}$$
$$= \frac{s_{0P}(1-s_P)^2 V_1^2 Z_m^2 r_2}{r_2^2 x_m^2\left(1 + 2\frac{x_1}{x_m} + s_{0P}\frac{r_1}{r_2}\right)^2}$$

Taking now $Z_m = x_m$ (approximately), and assuming that $\cos\phi_0 = 0\cdot 2$ and $\cos\phi_k = 0\cdot 75$, we have

$$P_{max.} = \frac{s_{0P}(1-s_P)^2 V_1^2}{r_2\left(1 + 0\cdot 68\tau + s_{0P}\frac{r_1}{r_2}\right)^2} = \frac{s_{0P}(1-s_{0P}) V_1^2}{r_2\left(1 + 0\cdot 68\tau + s_{0P}\frac{r_1}{r_2}\right)^2}$$

Similarly a simplified expression is found for $T_{max.}$

By taking nominal values for the various impedances for various values of τ the power factor may be calculated for successive values of s, thus establishing the curves given in Figs. 11, 12, and 13. In the same way the power output at each slip value may be determined, and by plotting these values on a curve the maximum power is obtained. Thus the various power values may be expressed as a percentage of the maximum. Also, by calculating for each value of τ the maximum power from the approximate formula

$$P_{max.} = \frac{s_{0P}(1-s_P)^2 V_1^2}{r_2\left(1 + 0\cdot 68\tau + s_{0P}\frac{r_1}{r_2}\right)^2}$$

and equating the results to the corresponding maximum values using the more correct expression, the correction factor C_P is obtained.

From the values established in calculating the power-factor curves extended to $s = 1$ the primary current is arrived at, and then by equating to the values given by the formula $I'_k = V_1/Z_t$ the correction-factor curve (Fig. 6) is obtained. Curves A and B in Fig. 6 are based on the assumption that the secondary and primary resistances are equal, while for Curve C the assumption is that the secondary resistance is twice the primary. The latter is generally the case to a close approximation where starting is effected by means of resistance in the starting phase (the ordinary split-phase motor). When the machine is of the capacitor-start type it is often possible to make the secondary resistance as low as the primary. In any event it is clear that for intermediate cases it is possible to interpolate between the two sets of curves.

In both cases the assumption is made that $x_1 = x_2$. Again from the values calculated for $s = 1$ the actual short-circuit power factor is obtained, and by equating this to the "apparent" value where

$$\cos\phi_k \text{ (apparent)} = \frac{r_t}{r_t + jx_t}$$

the C_ϕ correction-factor curves are obtained.

DISCUSSION BEFORE THE INSTITUTION, 19TH JANUARY, 1939

Mr. D. B. Hoseason: In monetary value, the f.h.p. motor must to-day constitute a very important section of the total output of electrical manufacturers. The production of f.h.p. motors in the United States is even greater than in Great Britain, and probably gives an indication of what may develop in this country in a few years' time. Hence every effort should be made to place the design of these machines on a rational basis, even though taken individually they may be relatively unimportant.

Equation (12) in the paper gives the end-winding length of stator coils. It seems to me that P_e corresponds to the radius of the curved portion of the coil, and therefore we have

$$l_e = c\left[\pi P_e + (P_s - 2P_e)\right]$$

The straight portion of the coil end corresponds to $(P_s - 2P_e)$.

In connection with the efficiency values of small motors, the author states (page 169) that for a ¼-h.p. 1 400-r.p.m. split-phase motor the difference between the efficiencies established by a break test and by a summation-of-loss test might be 2 points. The inference is that the brake-test value would be somewhat higher than the summation-of-loss value, because of the reduction in magnetizing current between no-load and full load. My experience, however, is that the brake test gives a lower efficiency than the summation-of-loss test, and in the case of f.h.p. motors it is often very much lower—as much as 5 points in some cases.

In the Appendix, on page 177, a formula is presented for the maximum horse-power. I have had difficulty in relating $0 \cdot 68\tau$ to the corresponding item in the previous equation, namely $2(x_1/r_2)$,* and similar difficulty in relating that to the $2r_2x_1$ which appears immediately above it.

Much of the experimental work which has been done in the past on slot combinations has been carried out with inadequate apparatus, so that the results have been misleading and, in some cases, conflicting. I do not agree with the author's statement that a motor which will accelerate quietly has an accelerating characteristic free from any tendency to crawl due to subsynchronous torques. A number of motors have been tested which, when thrown on to the supply, accelerate silently, and yet have pronounced harmonic torques.

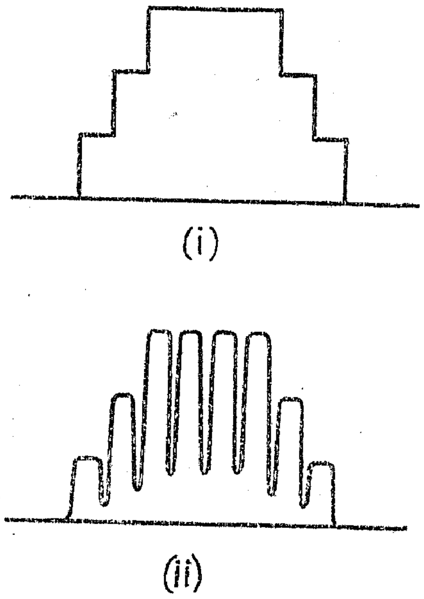


Fig. A.—Typical m.m.f. diagram (i) and flux form (ii) of an induction motor, showing marked influence of slot openings (semi-closed slots).

Part of the trouble associated with the acceleration of induction motors is due to an excessive tendency to apply mathematics. It is frequently assumed that the space field of an induction motor is of the form of a sine wave, with a flattened or a slightly pointed top, according to the type of winding distribution employed. The designer knows that, in fact, on account of the slotting, his magnetomotive-force diagram is of a stepped character, and is far from being a sine wave (see Fig. A). The actual flux form is even more distorted and can be resolved into a harmonic series, in which there are two main predominating harmonics, of numerical order $(2q + 1)$ and $(2q - 1)$ respectively, where q is the number of slots per pole. To obtain a squirrel-cage rotor which shall be non-responsive to any one harmonic, it is only necessary to put in squirrel-cage bars at the places shown in Fig. B. The harmonic voltages in each bar will then be in the same direction, and there will be no return path for the harmonic currents. At first sight it seems impracticable to select a number of bars for a squirrel-cage rotor which will not react to all the harmonic fields, on account of the large number of harmonics present. If we discard our mathematics, however, the problem is not so insoluble as it may at first appear. It is possible to skew the rotor bar through one stator slot pitch (Fig. C), thus obtaining a condition in which the effect of the slot opening, the principal cause of the trouble, is always the same. We have demonstrated by experiment that if a squirrel-cage rotor is skewed one stator slot pitch—not one rotor slot pitch, as is usually stated—it is possible to produce a speed/torque characteristic which is non-responsive to all the more important stator harmonic fields. It is necessary to go one stage further, however, and to insulate the bars, otherwise even though the bars are skewed, harmonic currents will flow, leaving the bars and returning through the laminations. Has the author any experience of the insulation of squirrel-cage rotor bars on f.h.p. motors, and, if so, what have been the results?

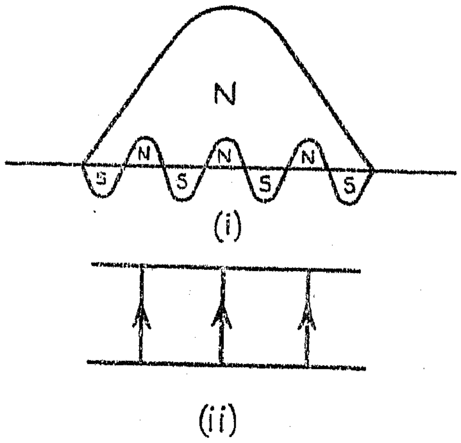


Fig. B

(i) Fundamental and one predominating harmonic of an induction-motor field.
(ii) Developed squirrel cage with one bar per pair of harmonic holes.

If the rotor bars are skewed and insulated to deal with subsynchronous harmonic torques, the designer is left free to select the number of bars which will give the quietest operation in service. Where did the author's recommendation for the number of rotor slots (page 165) originate? The suggestions include slot combinations which will be quiet in operation, but they also include others which our experience indicates will not be quiet. One almost infallible combination from the point of view of noise, which has the support of various authorities, is that the number of rotor slots should be equal to the number of stator slots plus twice the number of poles.

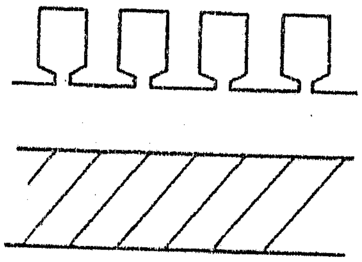


Fig. C.—Developed squirrel-cage rotor skewed one stator slot pitch, in which the influence of stator slot openings on individual rotor bars is constant.

Mr. A. G. Salisbury: I think that this paper will assist materially in exploding the fallacy that the f.h.p. motor is designed by hit-and-miss methods. The f.h.p.

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* Corrected for the *Journal*.

motor is a very important piece of electrical machinery, occupying a prominent place in the electrical industry, and if it is to be reliable, as much careful thought must be given to its design as is given to the design of larger motors. The domestic refrigerator and the cinema projector are examples where f.h.p. motors are invariably used and where a breakdown of the motor would be disastrous. It would be regrettable if any tendency to reduce costs and dimensions were carried so far as in any way to detract from the exceptional reliability of the f.h.p. motor.

The capacitor motor has almost ousted the repulsion-induction motor, as it has a simpler construction and is more reliable. The tendency is more and more to reduce the size of the condenser, and it would be of interest to have the author's views on how far this policy can be safely pursued.

The author states that the use of enamelled-wire stators is almost general. Until the art of enamelling wire is still further advanced I would hesitate to adopt this as standard practice, merely for the sake of getting a little more copper into the slots and possibly cutting down the size and cost of the frame. I think that the use of silk and cotton as an additional covering tends to protect the enamel from abrasion, and assists the bondage with the impregnating varnish. I should like to have the author's views on this point.

Another tendency, following American practice, is to build into every motor a thermal protective device. This is an additional device which may possibly go wrong and requires most careful adjustment and very delicate setting; otherwise the motor may cut out unnecessarily and be the cause of service calls, with inconvenience and expense. The present-day motor is so reliable and has such a high overload capacity that I think that the need for such an additional complication is rather debatable.

The author describes the advantage of annealing laminations, and I should be interested to have his opinion as to whether it is better to do the annealing at the lamination stage or on the complete stator or rotor. I imagine that if the annealing is carried out in the lamination stage the oxide which is produced takes up a certain amount of room and will possibly detract from the amount of iron in a core of given length. I should like to have the author's views on this.

Mr. J. E. Macfarlane: My experience shows that on both 3-phase and single-phase induction motors skewing the rotor bars one stator slot pitch assists materially in reducing the noise. Some years ago I had the task of taking existing 3-phase designs and adapting them for single-phase working. Many combinations which were useful on 3-phase turned out quite successfully on single-phase, and one combination which was used—36 slots in the stator and 41 in the rotor—we found quite satisfactory on 1- and 3-h.p., motors at 1 500 r.p.m., synchronous speed 50 cycles per sec.

With regard to equation (1), can the author give any recommendations for splitting up the product D^2L?

So far as the building-up of cores is concerned, I think that the use of an opening in the top of the rotor slot helps matters, as one then tends to obtain a smoother core.

In Table 3 I think that the figure given for K_d for 36 stator slots, coil pitch 6–13, should be 0·96, not 0·97.

I should be grateful if the author would indicate the meanings of the symbols used in equation (22).

On page 173 it is stated that in the split-phase motor the starting winding has approximately the same number of conductors per coil as the running winding; I am not sure what this means, because in making single-phase motors we generally used to put about twice as many conductors per slot in the starting winding as in the running winding. I should like to know what method of connecting the starting and the running windings is used and found most satisfactory by the author. One can put the main and the starting windings in parallel; another connection, which I found more satisfactory, was to put the main winding and the starting winding in series and shunt the starting winding with a resistance. With regard to the type of wires used, I should like to ask whether the author has had the opportunity of using paper-covered enamelled wires.

Mr. H. G. Poxon: I agree with Mr. Salisbury in that I do not consider that enamelled wire is satisfactory, except for the rather cheaper-quality motors. I should like to know whether the author would choose enamelled wire if cost were not the deciding factor.

Secondly, I think he will find that his equation (1) does not apply to motors of very much less than $\frac{1}{4}$ h.p. It will be seen from that equation that a motor where D^2L is less than 25 will have no output at all. It would be interesting to know whether the author can put forward a formula which will apply to these smaller motors.

Dr. E. Rosenberg: Like the author I have had excellent experience with enamel-covered wires, and I would mention that several manufacturers now produce enamel-covered wire which is more satisfactory than cotton-covered. It is possible to expose two enamelled wires pressed against each other to 1 000, 2 000, and even 5 000 volts, whereas with cotton covering this would be quite impossible. The use of enamel-covered wires not only cheapens but also improves the performance of the motor, because it means that part of the slot which would otherwise be occupied by combustible insulation is occupied by copper.

On page 161 the author mentions that standard designs of f.h.p. motors have ratings of $\frac{1}{8}$, $\frac{1}{6}$, $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$ h.p.; thus the ratios between any one output and the preceding one are 1·33, 1·5, 2, 1·5, 1·33, respectively, if 1 h.p. is the next size. A designer could design a series of motors very much better if these ratios were all the same, and "rating up," due to improvements in material or construction, would not necessitate different steps for each individual frame. Such improvements may be due to lower tolerances in bare and insulated wires or punchings without burrs. The replacement of cotton-covered by enamelled wire made it possible, with a certain series of motors, to obtain with every frame the output of the next bigger frame.

I should like to ask whether it pays to make one motor for an output of $\frac{1}{8}$ h.p. and another for $\frac{1}{6}$ h.p. If one uses a core of the same diameter for both, and allows a longer core for the larger machine, I believe that the factory cost will be the same in the two cases.

As regards the author's formula for the slot ratio necessary for the prevention of noise, this is not a complete solution to the problem any more than are the other formulae which have been put forward. He says " Where a compromise is necessary, it may be taken that the nearer the numbers N_1 and N_2 are to two of the ' harmonics ' the better. . . ." This means that if a compromise is necessary, then one has to guess.

I do not agree with Mr. Hoseason that skewing the rotor slots by one stator pitch will eliminate noise in all cases. Insulating the rotor bars is too costly an expedient, especially since it reduces the rating of the machine appreciably. I do not like the author's term " super-silent machine," because very frequently what appears on the test-bench to be an absolutely silent machine will not appear so in a hospital, an assembly room, or a private house.

The author says that a satisfactory winding factor will be found to be 70 %, and it would be interesting if he would tell us what, for different ratings, the complete factor is between the aggregate of all the actual copper wires and the slot area.

Mr. E. S. Ritter: With reference to the formula shown on page 176 for the current I_1, should not the expression in the numerator read $V_1(Z_m s_0 + 2Z_2)$? If so, the expression three lines lower down should read

$$V_1\left[(s_0 r_m + 2r_2) + j(s_0 x_m + 2sx_2)\right]$$ [*]

Mr. H. J. Eley: I should like to ask the author whether he has any reliable information regarding the relationship which is necessary between the number of slots per pole on the rotor and the stator and the maximum or limiting induction density in the air-gap, to ensure reasonably silent running.

With regard to the remarks on page 162 relating to annealing, it would be helpful if the author could confirm that, provided the stampings are annealed after punching, planishing for the sake of removing burrs can be omitted with impunity.

Does the author consider that there are any advantages to be obtained from the external-rotor type as compared with the internal-rotor type of f.h.p. motors, more particularly when cast-aluminium rotors are used? I refer particularly to specific starting and accelerating torques and overload capacities.

As the author made no reference to 2-stage windings on the rotors of f.h.p. motors it will be useful to have his views on the relative advantages and disadvantages of such designs as applied to f.h.p. motors.

Also, in view of the trouble which is experienced from time to time in bulk manufacture with lack of uniformity in the joints of the ordinary copper squirrel-cage, I shall be interested to know whether the author can confirm that more satisfaction can be obtained with the sintering process on powdered-copper rotors.

Dr. J. E. Parton: At the present time there is a demand for a f.h.p. single-phase synchronous motor for use as a teleprinter drive. Since the various sections of the grid system are now running interlinked, the use of such motors would ensure equality of speed of both transmitting and receiving teleprinter mechanisms without the necessity of frequent adjustments, as with d.c. drives. 3 000-r.p.m. synchronous motors of the capacitor type have been tried out, but it would appear that their limitations are poor starting and synchronous torques, pronounced sub-harmonic torques, and excessive heating.

Although the paper deals primarily with f.h.p. induction motors, it would be helpful if the author could indicate the main lines along which these difficulties with small synchronous motors could be overcome.

Mr. G. E. Middleton: Since f.h.p. motors are so comparatively small the designer of such machines has to know far more intimately what is going on inside them than has, say, the designer of a 10 000-h.p. motor. The f.h.p. motor has to be, if anything, more reliable than the large induction motor, because frequently-multiplied cases of trouble cannot be tolerated. Not only that, but it has to be manufactured to a cut price.

I have checked equation (1) for a machine of approximately ¼-h.p. size and also for one of 1-h.p. size, and have come to the conclusion that I should not like to have to build a machine down to those dimensions and guarantee reasonable overload capacity, under existing labour conditions. Several very successful single-phase induction motors have been manufactured with rotor diameters of the order of ¾ in., and, though they are based on the same principles of design as the 10 000-h.p. motor, they hardly come within the scope of equation (1).

The question of noise has been referred to at some length. In this connection it must be remembered that the average f.h.p. motor is a single-phase motor, and a single-phase motor which is running on one winding only inherently develops a torque pulsation at twice line-frequency, which is reflected back into the stator. Unless the stator is mounted so as to absorb such torque pulsations, the vibration set up may be transmitted into the supporting structure. Proper resilient mounting, or an attempt to turn a single-phase motor into a machine with a polyphase noise characteristic, are the only ways of overcoming the trouble. If it were possible to approximate to 2-phase conditions we should be able to take a large step forward in the direction of a quiet motor, but even then we should still have the problem of slot combinations and skewing, where there is plenty of experience with larger motors to guide us.

There is nothing very novel about equation (3); it merely says that the difference between the number of stator slots and the number of rotor slots shall be some multiple of the number of poles, a fact which is not unknown to the designer of polyphase machines.

Dealing with the use of enamelled wire, in my experience the figure of 70 % referred to by the author is rather high; if one is going to cram that amount of enamelled wire into a slot, and then impregnate it with a varnish which is to protect the wire both mechanically and electrically, one may have trouble due to the impregnating varnish softening the enamel of the wire. If this occurs, two wires crossing each other under mechanical pressure may tend to squeeze out the enamel film between them. Even if a machine in which there is such a fault passes the factory test, it may be a potential source of trouble once it is put into service. It is therefore advisable to provide some mechanical protection to the enamel, by covering it with cotton, silk, or even paper, if this can be wound satisfactorily.

In my experience, the copper-bar rotor is splendid from an electrical point of view, but it is difficult to manufacture satisfactorily because the operators will not take sufficient care of the joints. There are two joints per bar, and a faulty joint means a noisy motor. The cast-aluminium rotor is open to certain objections, but if these are overcome (as they can be) by the use of proper casting machinery, there seems to be no question that the aluminium rotor is superior to the copper rotor as regards performance, as well as from the manufacturing standpoint.

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[*] Corrected for the *Journal*.

The author emphasized in his opening remarks the figure of 0·64 for the distribution factor in a squirrel-cage rotor, but he omitted to give the formula for rotor resistance, which presumably would include the distribution factor. If we consider that the single-phase motor operates as if it contained a forward-rotating field and a backward-rotating field, then as far as the forward field is concerned all the well-known polyphase equations apply, and the figure of 0·64 in the rotor-resistance formula does not arise. In Section (13), when developing a formula for the length of end windings, the author goes to some trouble to add on a factor in equation (13) of

$$0{\cdot}07\,\frac{\text{Rotor diameter}}{\text{Core length}}$$

But the ratio of the rotor diameter to the core length does not vary very widely with machines of normal capacity, and he is putting the designer to the trouble of finding out this factor so that he may add on 1 % or 2 % to the length of an end winding, which is only an intelligent guess in any case.

Another criticism which I should like to make, is of the method of evaluating the output, in that almost all the author's curves are based on the average values given in Section (20). Those average values apply to machines of the order of $\frac{1}{4}$ to $\frac{3}{4}$ h.p., but not very much above or below that range. I should like the author to give some indication of how much those curves would be modified if we assumed a power factor of, say, 0·85 for the short-circuit condition. It seems to me fundamentally wrong to base design factors on an assumption of that type, in view of the simplicity of the ordinary equivalent circuit, giving more exact treatment.

(*Communicated*) The figure of 0·637 in equation (16) is not justifiable for straight-sided slots with rounded bottoms. It would be more accurate to take a figure of approximately 0·2; or easier to omit this factor and regard d_3 as the full depth.

Turning to Section (18), I should be interested to know how a value for σ can be determined.

As regards Section (19), I do not appreciate the basis of the factors 1·59 for the core density, and 1·24 for the teeth, as the flux formula has already given the peak a.c. value of flux. It is presumed that the factor 3 which multiplies the tooth volume in equation (35) is purely empirical.

In my opinion the design sheets referred to in Section (22) could be better laid out by putting all the general information for a line of machines on one sheet, and the particulars referring to a specific rating on another sheet for quick recording of new ratings.

The author does not indicate how the voltage on the starting condenser of a capacitor motor is controlled.

Mr. R. S. Blackledge (*communicated*): In the author's discussion of the clearance between rotor bars and slots, there is mentioned a skew equal to twice the (rotor) slot pitch; for normal slot ratios this value is rather high, and I would ask whether any marked advantages attend the use of it, for there are several disadvantages.

There are two departures from what surely is standard terminology; the distribution factor is symbolized by K_d, which is usually associated with the eddy-current loss factor, whilst the expression "winding factor" is used to denote what might well be termed "slot space factor." The term "winding factor" has hitherto always been associated with one or another of the electromotive-force coefficients.[*]

It would be interesting to know how the author's slot-ratio criteria were established empirically. The expression given would appear to be a particular case of a more general theorem due to Hildebrand;[†] clear analyses of the conditions necessary and sufficient for magnetic unbalance had been given by Chapman[‡] and Creedy[§] prior to the publication of Hildebrand's paper. A slot-ratio formula which differentiates machines having excessive noise-levels from those having tolerable noise, will not necessarily adjudicate between tolerable noise and super-silence; the criteria due to Hildebrand seem to cover some cases, but not all.

One may think of the noise level of an induction motor running light at normal voltage as being divisible into two broad belts: (*a*) the equivalent transformer noise, which is almost negligible on small machines of good design; and (*b*) the components due to several causes all of which, *ipso facto*, can be credited to the presence of the slots. In connection with (*a*), there is much of interest in a recent paper[‖] in which C. A. Mason points to magnetostriction as a factor. Clearly, as one increases the size of the magnetic circuit in order to reduce the induction, so is it necessary to take particular care of the clamping arrangements.

In f.h.p. machines there is, as the author comments, an appreciable difference between the terminal and induced voltages; in consequence, neglecting noises due to electric loading, a machine could conceivably comply with the silence specification on full load yet fail on light load. Is it the practice of the author to cover the two conditions—in which case the core volume would be increased approximately as the ratio of those two voltages—or is the nature of the drive taken into account? In the case of a fan or pump drive, for example, the motor cannot attain light-load conditions on site, and hence the cost of covering this contingency would hardly appear to be justified.

Previous to about 1926, most British designers were using odd numbers of rotor slots for squirrel-cage machines, and it is not difficult to turn up a precedent for the use of all odd numbers from 23 to 91, with the primes having greatest favour; nevertheless, the experiments of Stiel[¶] had more or less proved the desirability of the use of an even number. It is interesting to note—though possibly it is a misprint—that so far back as 1910 Hobart* quoted the case of an 8-pole, 3-phase, squirrel-cage design having 96 stator and 144 rotor slots.

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[*] Miles Walker: "Specification and Design of Dynamo-Electric Machinery," footnote to p. 112; and S. Parker Smith: "Papers on the Design of A.C. Machinery" (Hawkins, Smith, and Neville), p. 23.

[†] *Transactions of the American I.E.E.*, 1930, vol. 49, p. 848; and W. R. Appleman: *ibid.*, 1937, vol. 56, p. 1359.

[‡] *Journal I.E.E.*, 1923, vol. 61, p. 39.

[§] "Theory of Electrical Machines," p. 115.

[‖] Paper No. R.L.P. 139, issued by the B.T.H. Research Laboratory, Rugby.

[¶] *Zeitschrift des Vereines deutscher Ingenieure*, 1921, vol. 65, p. 147.

The author's constants for the calculation of the flux-densities and magnetizing currents are new to me, but from Section (19) I gather that he calculates the flux at a point removed from the pole centre by 36 electrical degrees, as compared with the 30 degrees used by Max Kloss. A little further information as to the reason for this would be of value. Should not the constant in the denominator of the expression for the magnetizing current for the 3-phase case, assuming the angle is as stated above, be 2·09?† Independently of the datum angle θ, it would appear to be incorrect to take similar ratios of B_θ to B_{MEAN} as holding for single-phase and 3-phase excitation.

Neglecting chording and distribution, let us write

$$\text{Magnetizing current} = \frac{\Sigma\overline{\text{A.T.}}}{Nq_1z_1} \quad \text{and} \quad \frac{B_\theta}{B_{MEAN}} = M$$

We then obtain the comparison shown in Table A.

Table A

Authority	θ	M		N	
		Single-phase	3-phase	Single-phase	3-phase
Kloss	degrees 60	1·57	1·28	0·74	2·12
Parker Smith ..	60	—	1·36	—	2·23
Saunders, σ = 15 %	54	1·28	1·28	0·87	2·22
Saunders, σ = 10 %	54	1·28	1·28	0·84	2·22

The author's expressions for slot permeance, except in the case of the circular slot, are incorrect; that is, equations (16) and (17) need to be revised.

Mr. F. E. Butcher (*communicated*): Under the heading "Slot Ratios" the author gives a method for determining the silent-running qualities of various slot ratios. It would be interesting to know whether the method has any mathematical derivation, because whilst I agree that numbers shown by the method to be "good" would turn out to be so, my experience shows that there are numerous other "good" ratios that would not be satisfactory according to the author's method. I do not think that the noise problem is sufficiently simple to be wholly covered in this way.

I cannot agree with the author that all quiet slot combinations are free from cogging or harmonic crawling tendencies.

I do not agree with Mr. Salisbury that American design and manufacturing methods should not be copied. I have worked with and for both English and American companies of good repute and am proud to admit that I have learned—and still am learning—much from the Americans; and I believe that much also could be learned by others in this country.

Mr. G. H. Rawcliffe (*communicated*): The rule which the author gives for the slotting of f.h.p. motors, namely

$$N_1 \text{ or } N_2 = 2(p \pm \delta)$$

and which he states is "largely empirical" seems to be too logical in form to have no logical basis in fact; and I should like to submit the following for his consideration.

The harmonics in field forms may be divided into two groups: First, those which would arise from the distribution of the windings, saturation, etc., even if the number of slots were infinite. (These fall off rapidly in magnitude with increase of order, and thus only those of low order —3rd, 5th, 7th, and 9th, say—are of any importance.) Second, the slot harmonics which are higher in magnitude, and in order except with very few slots per phase. Slot harmonic fields of different orders on stator and rotor produce what may be called "interference bands" with each other, and these are distributed round the air-gap except in the single case where the orders of harmonic differ by unity. In this case there is unbalanced interference, with consequent noise and crawling.

The number of "beat cycles" between two sets of harmonic poles will be equal to the difference in the numbers of harmonic pole-pairs; that is, since one slot corresponds to one harmonic cycle, the number of beat cycles is equal to the difference in the numbers of slots (δ) on stator and rotor. More exactly, we may say:—

Number of stator slot harmonic pole-pairs $= p(2n_s \pm 1)$,
Number of rotor slot harmonic pole-pairs $= p(2n_r \pm 1)$,

where n_r = rotor slots per pole,
n_s = stator slots per pole,
and p = number of pairs of poles.

Hence, difference in harmonic pole-pairs

$$= (2pn_s - 2pn_r) = \text{Difference in total slots} = \delta$$

Hence if this difference is made equal to the number of pole pairs the effect of slot harmonics is eliminated.*

It may be arranged, however, that the beat cycles obtained between the slot harmonics react further with some of the non-slot harmonics, and if they do it is desirable that the second resultant shall still give a number of beat cycles equal to, or some multiple of, the number of pole pairs. This will still give symmetry with respect to the poles. Now if N is the number of harmonic poles of some order, we have, according as $N/2$ is greater or less than δ,

$$\frac{N_1}{2} - \delta = p \quad \text{or} \quad \delta - \frac{N_2}{2} = p$$

Rewriting, we have,

$$N_1 \text{ or } N_2 = 2(\delta \pm p)$$

which is the author's expression in a slightly different and better form. Here N_1 or N_2 will never be negative, whereas the author occasionally obtains negative signs and neglects them. The numerical values will be the same. Other harmonics besides those corresponding to this equation will have numbers of pole pairs which differ by twice the number of fundamental pole-pairs from those concerned in the equation. Hence the final interference patterns between all the harmonics will still be symmetrical whichever harmonics correspond to the value N_1 or N_2.

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* "Electric Motors" (2nd ed.), Table 65, facing p. 475.

† $\frac{18}{\sqrt{2\pi^2}} \sin 54°$.

* See L. H. A. Carr: *Journal I.E.E.*, 1936, vol. 78, p. 403.

It will be seen that this formula always gives an even number of rotor slots. δ must be even, since when $N/2$ is even p is even, and when $N/2$ is odd p is odd. δ, as before, is the numerical difference between the number of stator and the number of rotor slots. Thus this formula gives a high degree of symmetry between the resultants of the various harmonics, and might be expected to give a quiet machine with good speed/torque characteristic.

It has been asserted that a quiet machine will not necessarily be free from subsynchronous torques. This, if true, is at least consistent with the above, which only guarantees *symmetry* of the resultant harmonic fields. This tends to give a quiet machine. Subsynchronous torques depend on the *existence* of harmonic m.m.f. wave-forms. The magnitude of these may be reduced by interference, but the above formula, which is the condition for symmetrical interference with respect to the main poles, does not rule out the existence of harmonic wave-forms. This can only be done by proper distribution of the windings, which the author discusses. Slot-harmonic subsynchronous torques can, of course, be eliminated by skewing.

[The author's reply to this discussion will be found on page 188.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 23RD JANUARY, 1939

Dr. M. L. Kahn: The author restricts himself to dealing with the electrical design of f.h.p. induction motors, and makes only a few remarks on the mechanical design. Both are of importance, and in many cases constructional features and manufacturing considerations are the determining factor.

I gather from page 162 of the paper that the author builds up his design on the outside diameter of the stator core and its length, and not on the rotor diameter. I have always considered that this is the right way to deal with induction-motor design, and that the practice usually adopted in textbooks of using the rotor diameter is purely due to the fact that d.c. motor design was developed and fully understood before the a.c. motor took the field. The adoption of the stator diameter as the basic dimension has the advantage that it coincides with the determining feature of the types where this dimension is fixed and the rotor diameter can easily be varied.

To the remarks which the author makes on the air-gap I should like to add that for constructional and production purposes motors with too small an air-gap are to be deprecated. Certain advantages of output and efficiency are of course obtainable by reducing the gap to a minimum, but if the designer goes too far in that direction difficulties in production are bound to arise and the reliability of the machine is impaired.

I agree that aluminium rotor windings, which are now standardized by many firms for induction motors above 1 h.p., are, to say the least, of doubtful value for f.h.p. motors. It must be understood that, in the larger-size induction motors referred to, the determining factor for the output obtainable from a squirrel-cage machine is the stator. There is always surplus room on the active belt of the rotor, and this can easily be utilized for introducing material of lower conductivity than copper, e.g. aluminium. Moreover, the difficulties inherent in applying the conductive material in the rotor in the form of castings will naturally be minimized if the bars of the rotor are of reasonable size, as is the case with motors of larger outputs. If, as I feel sure is the case, greater consistency of test results on duplicate motors can be obtained with copper rotors than aluminium rotors for f.h.p. motors, this point may well be the determining factor in favour of copper rotors, as the total cost to the factory of rejects from test is always a very serious consideration.

Mr. H. Jack: In developing f.h.p. motors one should not modify a single-phase design so as to suit it for possible use on 3-phase supplies, as at least 90 % of the sales will consist of single-phase motors. Moreover, it is easy to get the same output from a given frame when it is to be used as a 3-phase motor.

As regards the question of adopting either circular laminations or a lamination shape suitable for a riveted frame, I am very much in favour of using circular laminations with a steel shell or die-cast shell around them. With the riveted-core type it is necessary to provide some sort of end flange which must be riveted on and machined up later, and although it would appear that better use is made of the steel by employing the square form in which it is provided, the advantages and disadvantages of adopting the riveted core need careful consideration.

I note that the author recommends the use of enamelled wire; I have for many years contended that, for motors in general, enamelled and cotton-covered wire is superior to double cotton-covered. The use of enamelled wire without cotton covering is probably quite safe in f.h.p. motors, because the voltage seldom exceeds 260 volts. Although enamelled wire is adopted generally in America, it does not follow that it would be equally suitable in this country: in America the prevailing voltage is 110 volts, whereas here we have supply voltages ranging from 200 to 260 volts.

Dealing further with core construction, the author does not recommend the use of low-loss sheet steel. My experience is, however, that it has many advantages—one can use thicker laminations and obtain a better space-factor in the core, and a lower cost of notching.

With regard to rotor construction, the author favours the squirrel-cage rotor with copper bars riveted to copper end-rings. I would point out, however, that a copper bar riveted over an end ring of thin copper sheet makes a very doubtful electrical joint. If one attempts to solder it with tin solder, it is difficult for the solder to get inside the joint, and soft solder is not very desirable. We have had to discard this type of joint on motors of 1 h.p. and above, and it is not more reliable on smaller machines. There is always the danger that as the machine gets older the quality of the joint between the bar and the end ring will get worse. One cannot always be sure that one is getting uniform current distribution with the copper riveted end-ring, and my experience is that the aluminium rotor, which has no joints between bars and end rings, is far superior.

Dr. Kahn suggested that aluminium is satisfactory for larger rotors but not so suitable for small rotors. Actually, the British Thomson-Houston Co., who were the first to adopt the cast-aluminium rotor in Europe, developed it for small rotors of about 1⅝ in. diameter, and after producing successfully about 50 000 rotors of this size adopted it for rotors up to about 13 in. diameter. If one uses aluminium of very high purity and takes all the necessary precautions it is surprising how near the resistance of the finished rotor approaches to the calculated figure. Properly-constructed cast-aluminium rotors give no trouble with hot joints, change of resistance with time, or incorrect current distribution in the bars and end rings.

The author states that 36 slots give a quieter machine than 24 slots, but that this effect can be offset by a sinusoidal distribution of the 24-slot winding. This argument is not sound, as it is also common practice to use a sinusoidal distribution with 36 slots. Further, some leading manufacturers now machine-wind the stators of f.h.p. motors and this enables them to get the advantage of the greater number of slots at low cost.

The author's rule with regard to slot ratios can be more simply expressed by stating that the difference in the slot numbers per pole should be a whole number, preferably greater than unity, and the rotor must be skewed one stator slot pitch. Many manufacturing firms now seem to be falling in with this general rule.

The use of sinusoidal distribution windings is now common practice with most makers. The British Thomson-Houston Co. have used sinusoidal distribution windings on f.h.p. motors for over 12 years, and on larger motors (up to 15 h.p.) they have used sinusoidal distribution windings for single-phase machines for many years.

The author states that for a squirrel-cage winding the distribution factor is 0·64. I do not think that this is correct, as the value depends on the distribution of current across any one pole, and since the current distribution in a squirrel-cage rotor is a reflection of that in the stator the distribution factor of the rotor winding must be approximately the same as that of the stator. With regard to leakage reactance, it seems to me that there is an error in the number 0·637 in equation (16), and similarly in equation (17) the number 1·274 appears to be incorrect. Equation (20), which is a special case of equation (17), gives the figure as 0·637; this is, I think, the correct value for equation (20).

In the latter part of the paper the author works out the theory of the machine from the work done by Steinmetz; I prefer to keep the stator reactance and resistance separate from the rotor reactance and resistance, and include the magnetizing reactance in the calculation of the impedance. In this way one eliminates the correction factors and apparent current and deals more or less with the real impedance and currents.

The author mentions capacitor motors, but he does not describe a method of calculating the capacitor voltage during the starting period. This is an extremely important factor from the design point of view. It would also have been useful if he had given some information regarding the characteristics of capacitor motors.

The question of the pulsating torque of a single-phase motor is not mentioned by the author. Very few people realize that the torque of a single-phase motor is anything but uniform, and if they mount it on a board which is resonant they are surprised to find that the board vibrates. Resilient mounting of single-phase motors is a great advantage from the point of view of reducing noise and vibration.

Dr. R. Pohl: It seems to me that the quality of the stampings used, and their insulation, are points of considerable importance. By using a high-grade material of greater thickness, is it not possible to get a distinctly better space-factor, and to increase the specific magnetic loading, and thus also the electric loading of the machine? In that connection, the smoothness and insulation of the stampings require constant observation, because the space factor is generally a good deal smaller than is assumed.

The author recommended enamelled wire for windings; did he mean wire which is both enamelled and single cotton-covered? Of course, material of that kind belongs to Class "A," and also requires to be impregnated. To use enamel alone, though its elasticity nowadays is remarkable, seems to me rather risky since a single short-circuited turn spells disaster (this applies to a.c. windings generally, though in a less degree to the smallest sizes). Would it not be possible to employ the new impregnated asbestos covering? It avoids the need for impregnating the completed winding, and would permit higher temperatures in view of the Class "B" quality of this material.

Again, as I have found on big machines, the question of avoiding air pockets considerably affects the rating. Assuming that suitable insulation is being employed on the wire, I do not see why one should not raise the limiting temperature and in that way increase the limit of possible power of a given size of machine. This remark applies to motors in general.

It would be useful to develop a method of calculating more accurately the ampere-turns required for streamlined teeth, because with very small air-gaps the magnetic reluctance of the teeth plays so great a part in the general performance of the motor.

Cast-aluminium rotors seem to be becoming general practice on the Continent. This practice, by eliminating joints between bars and rings, avoids a chief cause of trouble. Aluminium pressure casting requires special equipment and experience, but it represents an important improvement in the design of squirrel-cage motors.

Mr. W. M. Cranston: I am sorry that the author does not devote more attention to the effect which the manufacturing limitations have on the design which is finally chosen.

I am interested to see the author's comment on the use of enamelled wire for windings. We have used enamelled wire for a considerable number of years, particularly on repulsion induction-motor stators. More recently we have used it on split-phase machines, and since double-enamelled wire became available we have used it for the running winding on split-phase motors. I should like to know whether the author has any experience of this practice, as from his remarks it would appear that he would use ordinary enamelled wire on running windings or even on 3-phase machines. There we get a very much higher voltage-range in any one slot, and consequently a greater danger. We have used extensively wire insulated with paper and enamel, and had considerable success with it.

I notice that the author favours leaving the bore of the stator unmachined. While I agree that it is very desirable to get rid of the losses, on silent machines with high specific starting torque I have always been afraid of adopting an unmachined stator. Recently I had a chance to see something of American methods, and found that except with very rough machines a finishing process was applied to the stator. Curiously enough, broaching of the stator bore gave the accuracy required without pushing up the losses as occurs on the ground stator.

I agree with the author in his preference for the copper rotor, but it should be remembered that it is only economical if it is produced in large quantities. Aluminium rotors are cheaper unless very efficient bulk-production methods are adopted in the manufacture of the copper rotor. I have seen equipment for the production of copper rotors with welded rings which was almost entirely automatic.

Turning to the important question of silent machines, which are being used more and more for refrigerator work and all sorts of household appliances, I have come across a suggestion that it is of great advantage to rotate each stator plate relative to the next by, possibly, one slot; because the permeability of the iron tends to be better along the grain of rolling than across and further there is a slight taper on the plates, and these two factors are counter-balanced in building the stator. I should like to know the author's views on this matter.

In his comments on the building of stators the author refers to the scale left by annealing as being sufficient insulation between the plates. Providing the plates are annealed before building I am in favour of this system, but I should like the author to confirm that that is his idea.

On page 173 he refers to the condensers used on capacitor-start motors. There have been great improvements in electrolytic condensers during the past few years, and it is due to these improvements that the capacitor motor has risen to prominence. It should be fully understood, however, that the starting condenser is an exceedingly short-time-rated appliance, and if it is left in circuit for too long a period it becomes damaged owing to a rise of temperature. Can the author state the margin of safety that exists on the plain plate electrolytic condensers which are generally used in this country? The condenser manufacturers have recently evolved the etched-plate type of condenser. This has a great advantage in cost, but the drawback is that the rating of the condenser is only one-third that of the plain-plate type.

I agree with the author's note on the magnetic switch. I think that a properly designed centrifugal switch is the best solution for the problem of switching out the starting winding at the correct speed.

Mr. A. J. Mare: I regret that the author makes so little mention of the capacitor motor; I think he might have given some details of the calculation of the capacitance and voltage of the condenser for various types of motors. The small capacitor start and run motor is commonly in use for fans, and while the capacitance of the condenser is kept within reasonable limits there is a tendency for the voltage applied to become so high as to increase the bulk of the condenser; alternatively, the condenser is required to operate at a high temperature, which again means greater bulk.

Referring to the capacitor-start motor, the etched-foil type of electrolytic condenser has been made and used in the United States for some time, but only on 110-volt supplies. American manufacturers of f.h.p. motors for this country have not only to wind the motor for the higher voltage but to arrange a starting winding that gives a voltage below 160 volts, so that an American etched-foil condenser of 100 μF or thereabouts may be employed. This makes the winding of the motor more complex. British manufacturers, on the other hand, are able to employ etched-foil condensers designed for 275 and 350 volts, which enable them to wind the motor in a more straightforward manner. Perhaps the author has some comments to make on this development.

Dr. Pohl suggested that the insulation of the windings might be of asbestos so that the motors could be run at a higher temperature. I find, however, that customers who use f.h.p. motors are already grumbling at the large temperature-rise of these machines.

Mr. J. R. Henderson: In my view the basic design principles for f.h.p. machines are exactly the same as those for larger machines, but in applying these principles to f.h.p. machines it should be remembered that resistances are relatively much larger quantities and consequently approximations which are based on negligible resistance drop are not valid for smaller machines. Such machines exhibit one important difference: the spread or range of a batch is wider than with the larger machines, since the factors governing performance on test are all subject to wider percentage tolerances due to manufacturing variations. I have lately had occasion to examine large numbers of test figures by statistical methods, and have found that there is no reasonable doubt that the f.h.p. motor falls into the same category as other industrial products, such as those described in B.S.S. No. 600—1935. It follows from that that although we cannot predict in advance how many machines will be above a certain standard, if we have made a reasonable number of samples we can do so with a fair degree of certainty.

With regard to sinusoidal distribution of the ampere-turns, I first tried this out on the assumption that since the flux in any machine is produced by the resultant of two or more systems of ampere-turns, these component systems themselves should be as nearly as possible sinusoidal. This innovation led to a great improvement in the run-up torque, but did not at first appear to have much influence on noise. Attention to field form has, however, contributed largely to quiet running. The harmonics present in a stepped wave of ampere-turns can be calculated and by attention to correct distribution may, with two exceptions, be kept to a very low order. These exceptions are the $(m - 1)$th and $(m + 1)$th harmonics, where m is the number of stator slots per pole pair. Thus if a stator has 12 slots per pole pair, the 11th harmonic and the 13th harmonic cannot be eliminated by modifying the stator. The effect on the rotor can be largely reduced by skewing the rotor slot by one stator slot-pitch, and, as mentioned by Mr. Jack, this is a compromise. It is usually possible to hold the one stator slot-pitch skew within such limits as will reduce the $(m - 1)$th and $(m + 1)$th harmonics to negligible proportions.*

I agree with Mr. Jack's remarks on the use of low-loss iron. It is true that at high saturation the permeability of the low-loss material falls, but the difference at $B = 13\,000$ to $B = 13\,500$ does not amount to very much.

In conclusion, I am not in favour of the high current density mentioned by the author for the starting windings. A figure of 60 000 amp. per sq. in. seems rather high, and at this current density the copper temperature will begin to rise at the rate of 4 or 5 deg. C. per sec. This gives very little margin for contingencies, or even for testing. The heating is proportional to the square of the current density, and by working to slightly lower densities, even 25 % less, we halve the temperature attained in a particular time.

Mr. E. K. Bottle: In his Introduction the author lightly dismisses graphical methods of calculation. In my experience, however, the circle diagram, when correctly drawn, is far more convenient than the inversion calculation and can be made equally accurate for determining power factor and efficiencies. After analysing test-results obtained on a large number of motors ranging from a $\frac{3}{4}$-h.p. repulsion-start type to a $\frac{1}{20}$-h.p. split-phase machine, I have devised a method of constructing a circle diagram which gives a reasonably accurate forecast of performance. It is based on the following empirical relationships:—

(1) The locus of the ends of the current vectors corresponding to various loads is very approximately a circular arc bounded by a chord joining the no-load and short-circuit points.

(2) Maximum output occurs at the point of contact of the tangent parallel to this chord.

(3) If the chord is produced to cut the horizontal axis and a line is drawn through this intersection to the centre of the circle, then the distance from the maximum-output point perpendicular to this line equals the maximum output in watts divided by the voltage.

Calculation of no-load and short-circuit currents follows the principles laid down by the author. The maximum-output current referred to above is obtained from the formula:—

$$\frac{(\text{Actual short-circuit current}) - (\text{No-load current})}{2\left[1 + (\text{Short-circuit power factor})\right]}$$

Given these three values and the above relationship, the centre of the circle can be found geometrically by trial and error. It is actually geometrically indeterminate, but two or three attempts will usually give it. Thus, referring to Fig. D, draw ABC and MN. Select an arbitrary position for P on MN. Lay a straight-edge along CP and slide a set square along this till the correct value of DE is obtained. Mark D with centre P and radius PA, and test whether the circle passes through D. If not, repeat for another position of P. In the case of small machines this centre may come above the active component of the full-load current.

I must confess to some disappointment that the paper makes no mention of shaded-pole and capacitor-run types of f.h.p. induction motors. Future developments are bound up with these two types, and it is here that designers are most in need of guidance, because none of the simplifications which the author suggests seem to apply.

Mr. W. P. Richardson: In the Introduction the author deprecates the use of graphical methods and expresses a preference for analytical methods, but in my experience both have their uses. The graphical method, i.e. the circle diagram, is more simple and quite accurate down to $\frac{1}{4}$ h.p. for obtaining running performance figures. Its use gives the designer a physical check on the calculated quantities.

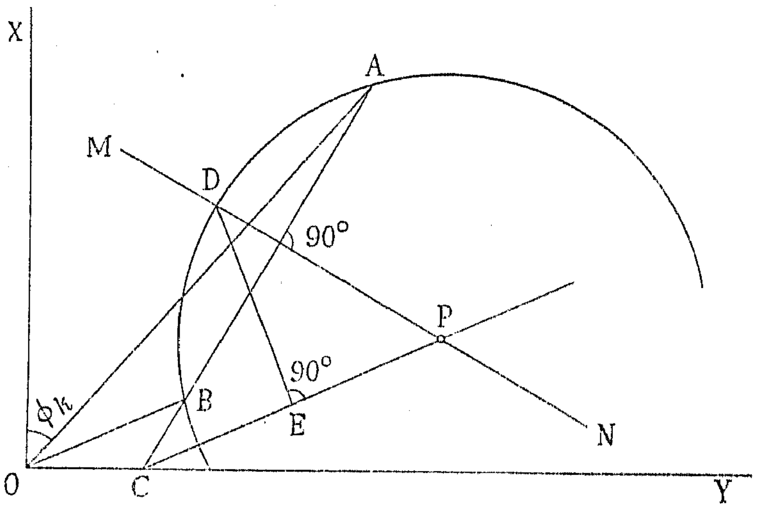

Fig. D

OA = short-circuit current,
OB = no-load current,
$DE = \dfrac{OA - OB}{2(1 + \cos\phi_k)}$,
$\angle DEP = 90°$
MN bisects AB.

The author states that the allowance for the stator drop represents the difference between the design of large and of small machines. This allowance for voltage drop and the influence of loss variation can be made by raising the centre of the circle above the baseline by an amount which is readily calculated from the magnetizing current, short-circuit current, and short-circuit power-factor. For example, one result obtained by this method on a $\frac{1}{4}$-h.p. 4-pole single-phase motor was a calculated power factor of 0·65 against a test value of 0·64.

With regard to the calculation of the speed/torque curve, analytical methods are preferable. It is curious how ideas regarding the question of slot ratios have changed with the passing of time. In addition to the slot ratio there are two factors which influence starting; the first is the skewing of the slots, and the second is that it is essential to provide enough resistance in the rotor to give a sufficiently good torque. If these two conditions are not satisfied, the best slot ratio will fail to give the results expected of it.

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* For some very useful tables dealing with field-form harmonics, see W. R. Appleman: *Transactions of the American I.E.E.*, 1937, vol. 56, p. 1359.

Equation (3), which agrees with that given by Hildebrand* for slot-difference harmonics, works well in practice; but the author makes one remark which seems to me to require some qualification, namely that the larger the numbers given by this formula the more satisfactory will be the slot ratio. Does he not set a limit to this? The formula will allow twice as many slots on the rotor as on the stator, but I think most designers of experience would prefer to avoid this. I myself keep to a maximum of about 50 % more.

With regard to the remarks about rotor slots in Section (5), I agree that all rotor slots should have an opening, as otherwise excessively high flux-leakage results. Some time ago, when working on a new design, I obtained the following rather puzzling result. With totally enclosed rotor slots the reactance obtained from a short-circuit test was 83 ohms, but when the slots were converted to 1-mm. opening the reactance dropped to 37 ohms, which was what I had been hoping to obtain. The effect of this lower reactance on the full-load power-factor was an improvement from 0·74 to 0·79.

As regards the question of finishing stator bores to size, it seems to me that if this is to be avoided then two conditions are necessary. Firstly, the bore and the outside diameter must be stamped out in the same operation; and secondly, the stator core must be built up on an inside mandril. If one is working with small air-gaps, the use of an inside mandril is very important.

Mr. H. Joseph: I notice that the author prefers to use plain enamelled wire for windings, whereas speakers in this discussion have mentioned other forms of insulation such as enamel and cotton and, in particular, enamel and paper. For the windings of these small motors I have successfully used wire insulated with enamel and paper. Obviously the space factor is altered thereby, but that difficulty may be got over. Paper- and enamel-covered wire can be had with a total of 4 mils covering (i.e. 2 mils radius). Dr. Pohl mentioned asbestos-covered wire; we have used this in larger motors, but not in f.h.p. motors.

My experience, especially from the maintenance point of view, is that the short-circuiting gear for cutting out the starting winding is a prolific source of trouble. Contrary to the author's statement on page 174, I have not yet come across a satisfactory centrifugal switch for this purpose. When these switches have been in operation for a time, particularly in dusty or damp situations, they stick and invariably the starting winding burns out. I have never before heard of starting windings being designed to reach, even momentarily, a current density of 60 000 amp. per sq. in. It is not surprising that such windings burn out easily. When we get trouble with a centrifugal switch we often replace it by a Twinob switch.

Mr. A. N. D. Kerr: The use of asbestos-covered wire has been mentioned in connection with the subject of temperature-rise; I do not think that anything which is going to make for a higher temperature-rise is a desirable innovation, because many customers consider that the temperature-rise of f.h.p. motors is far too high already. In fact, it may be said that small motors come into two categories: those in which the designer has had his way and the laminations are exposed, so dissipating the most heat; and those in which greater attention has been paid to what the customer wants and the laminations are in an enclosing shell, so keeping the external temperature-rise reasonably low. If temperature-rises are raised there will be a big outcry from the actual users of small motors, because these people like to feel that there is some margin in hand and that the motors will run reasonably cool in service. Judging by the reports of the service departments of small-motor manufacturers there is much to be said for this view.

With regard to the question of starting switchgear on single-phase motors, two solutions which are used by various firms are not referred to by the author. One is the Twinob switch and the other is the permanent-condenser method. The Twinob-switch method fell into disuse because the time of its operation was in the hands of the operator instead of being automatically governed by either current or accelerating torque, and therefore there were many cases where the time for starting was very long and the starting winding burned out. It was to obviate this difficulty that the development in automatic centrifugal switches took place. In the permanent-condenser method of starting, which is suitable for motors up to about $\frac{1}{4}$ h.p., and particularly the $\frac{1}{20}$- and $\frac{1}{8}$-h.p. sizes, a continuously rated paper condenser is left in circuit. The starting torque is relatively low, and the method is ideal for fan drives and other applications where a starting torque of less than full-load value is required.

Prof. W. Cramp: I am surprised to find that, except in manufacturing and mechanical details, very few changes have taken place lately in the design of f.h.p. induction motors. This is all the more remarkable when the improvements in materials are taken into account. Accuracy in the prediction of performance, however, has increased, and this will be still further advanced by the author's frank disclosure of his own methods. On the other hand, he sometimes appears to claim as novel, devices which are quite old. For example, he lays stress on the desirability of slots with rounded bottoms. I had adopted this plan in motors designed as long ago as 1906, because it seemed to me then to be an obvious method of increasing the electric loading without detriment to either efficiency, temperature-rise, or magnetic loading. I also used the same arrangement invariably in small d.c. machines, and I found that it paid well.

In the course of the discussion, references have been made to troubles with centrifugal switches. It was this difficulty that led me more than 30 years since to design and make a special form of motor, which to my surprise was not copied or developed by others until quite recently. A few years ago it was rediscovered and announced as something new by an American firm, and is now sold by their associates in England. It is a repulsion-induction machine, in which the repulsion winding lies nearest to the armature face, whilst the squirrel cage is below in a narrow part of the slot. The repulsion winding is connected to a small commutator with fixed short-circuited brushes. The result is that, as in the Boucherot rotor, at starting, when the slip is large, the repulsion winding is most effective and gives an excellent starting torque. As the speed rises the squirrel cage becomes more and more effective. Commutation gives no trouble; but it is necessary so to proportion the machine as to avoid racing at light load. If this is achieved, the behaviour of the motor is excellent; it starts easily against full-load torque, and I believe that the small commutator and brushes are a cheaper and more reliable device than any centrifugal switch.

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* *Transactions of the American I.E.E*, 1930, vol. 49, p. 848.

It is a little surprising that the machine, known as the Cramp single-phase motor,* has never been developed. It has a series characteristic and is very suitable for direct-driven variable-speed fans and pumps. From the manufacturing point of view it has the merit that armatures and field windings can be the same whatever the voltage, and it is only necessary to vary the primary winding to suit the system on which it is to be used.

Mr. A. Manighetti: I am interested in this subject in view of some difficulties which I experienced abroad some years ago with f.h.p. motors and their insulation. The motors were wound with enamelled wires, and the trouble was finally traced to the effects of the varnish solvents on the wire enamels. I should be glad to have the author's opinion of oil varnishes compared with synthetic-resin types, and to know which is to be preferred for treatment of enamelled-wire windings. It would be interesting to have some information on the treatment of deep, fine-gauge windings. These coils are troublesome in connection with varnish penetration, and complete drying-out to the core. The impregnated windings, when baked or treated in the oven, oxidize first on their surfaces; the solvent, being thus imprisoned in the interior of the coil, is liable to damage the wire enamels.

Does the author advocate the use of plain enamelled wires, or enamelled wires with added silk or cotton covering ?

Mr. S. F. Philpott (*communicated*): I should like to know whether the author can give any information on the influence of the casting pressure on the soundness and general quality of cast-aluminium rotors. Test results on large quantities of small rotors cast at 2 000 lb. per sq. in. pressure have been found to be entirely satisfactory, but according to one firm of repute in the die-casting business consistently non-porous aluminium castings can be obtained only by using a low pressure of about 80 lb. per sq. in. Another firm advocates a specially high pressure of 6 000 lb. per sq. in., and has put in special plant for working at this pressure.

I should like also to know whether there is any means of checking the electrical qualities of a rotor before assembly in the machine.

The author states that in this country it is quite common to use a magnetic switch to open-circuit the starting winding, but that provided the design is good a centrifugal switch is satisfactory and much cheaper. The use of the magnetic switch does not appear to be so popular as the author would have us suppose; the majority of split-phase motors made to-day have the centrifugal type of switch. As other speakers in the discussion have pointed out already, the centrifugal switch is the component of the motor most likely to give trouble—not necessarily on account of poor switch design, but because of the operation of the machine in unsuitable atmospheres, or because of the motor being run-up against such an overload that the switch-opening speed is not reached, with the result that both the contacts and the starting winding are burned out. A magnetic switch could be mounted in a sealed casing to overcome the first objection, and possibly a time-lag of a few seconds could be incorporated to overcome the second trouble. The magnetic switches fitted to some makes of small motor appear to be simple in construction and would not differ greatly in cost from the centrifugal type. It would be interesting to learn the author's opinion as to the performance, advantages, and disadvantages, of the magnetic switch.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON AND BIRMINGHAM

Mr. N. F. T. Saunders (*in reply*): I agree with Mr. Hoseason that the monetary value of the f.h.p. motor to the electrical industry is important, and that therefore there is every reason why the design of these machines should be given due attention. What is often lost sight of is that it is frequently necessary to commence the manufacture of a large quantity of motors to a particular design without first making a trial machine, and by the time a mistake is found in the design, hundreds of them may be in an advanced state of manufacture.

The difficulty with regard to equation (12) arises from the fact that the symbol P_e represents the maximum projection of the end winding (i.e. the outside of the outside coil), since this is the figure required to fix the dimensions of the end bracket; and I have taken $P_e/2$ as the projection of the mean coil.

It is interesting to note that Mr. Hoseason has had disappointing results from brake tests on f.h.p. motors. I can only report that I have not had a similar experience. It is, of course, not easy to get either good or reliable results from brake tests on such machines unless great care is taken and the tester has had a great deal of experience.

To clear up Mr. Hoseason's difficulty, I give below the intermediate stage in the derivation of the expression for maximum horse-power (for the case $r_2 = r_1$):—

$$(r_2x_m + 2r_2x_1 + s_{0m}x_mr_1)^2$$
$$= r_2^2x_m^2\left(1 + \frac{2x_1}{x_m} + s_{0m}\right)^2$$

And when $\cos\phi_m = 0\cdot2$, $\cos\phi_k = 0\cdot75$, and $x_1 = x_2$,

$$\frac{x_1}{x_m} = 0\cdot34\tau$$

I am aware that a machine which is quiet may have " harmonics " in the speed/torque curve, but I think it will generally be found that the tendency to crawl is not very marked, and to this extent the speed/torque curve may be described as " good."

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* See *Electrical Review*, 1907, vol. 61, p. 240.

I entirely agree with the statement that rotor slots should be skewed one stator slot pitch, but I have found that this does not guarantee freedom from trouble even with insulated bars. It is, of course, not economic to insulate the rotor bars in f.h.p. motors; but, as a matter of interest, I have made motors with insulated bars which did show kinks in the speed/torque curve, while when the bars were connected in single loops having a span exactly two-thirds of the stator pole pitch, the main kink was removed.*

I am frankly unable to give a precise origin for the expression (3), but I disagree with the various authorities who maintain that a rotor having a number of slots equal to the number on the stator plus twice the number of poles, will be noisy. For instance, the combination 36/48 is quiet on 6 poles.

I agree with Mr. Salisbury that reliability is an extremely important feature in f.h.p. motors, and I would add that this is the more necessary since such machines are often left running unattended, without anything equivalent to the protective switchgear which would be, as a matter of course, installed with a larger motor. This has a bearing also on the question of the built-in thermal overload device. I have used many hundreds of the device which contains a bimetal disc influenced by a heating coil in series with the motor current, and have not yet found a case where the device itself has failed. On the other hand, I have come across many cases where this device has probably prevented very serious trouble. In the case of a domestic refrigerator which is frequently left running in an empty house, I consider that the fitting of such a device should be compulsory. It must be borne in mind that the object of motor protective gear is often considered to be the prevention of damage to the supply lines, or the equivalent, whereas in f.h.p. motors, where this is a remote contingency, the primary consideration is consequential damage. A very small motor may start a very big fire if it develops a short-circuit and is left on the supply.

On the other hand, great care must be taken to distinguish between the device which resets itself automatically and that which must be reset manually. The former, for instance, would be extremely dangerous on a washing machine, while it should undoubtedly be used on a refrigerator; since a condition causing the motor to stall may clear itself, in which event the motor would restart and a service call would be avoided.

I think the extent to which the size of condensers may be reduced is a matter which is best left to the condenser manufacturers. I would, however, mention that extremely reliable electrolytic condensers are available in which very small dimensions are obtained by the use of etched foil.

I have no hesitation in recommending the use of enamelled wire as standard practice. The material now available leaves little to be desired, and designers should not allow themselves to be influenced by the disappointments which are almost inevitable when it is first used by people who have had no experience in handling it.

I would recommend the annealing of laminations before building up. As is suggested in the paper, the oxide which forms may be used as the insulation between them, and such oxide can be regulated so as to be as effective as a thicker layer of the usual material.

I do not think much purpose would be served in giving Mr. Macfarlane any recommendation regarding the splitting-up of D^2L. In practice the designer will invariably find that D is fixed by " commercial " considerations.

The meaning of the symbols used in expression (22) will be found by referring to Fig. 3.

If Mr. Macfarlane works out a design for a split-phase motor giving a starting torque of about $2\frac{1}{2}$ times full load, which is the fashion nowadays, I think he will be unable to avoid having about the same number of turns per coil in both windings.

Again, for the same reason, it will be found necessary to connect the two windings in parallel across the supply.

I have used paper-covered enamelled wires on medium-size motors (say, 1 to 10 h.p.) and found them excellent.

I am grateful to Mr. Poxon for giving me the opportunity to remedy an omission. I should, of course, have made it clear that equation (1) was not intended to apply to motors of less than $\frac{1}{8}$ h.p. at 1 500 r.p.m. (synchronous). As pure split-phase motors are not common below this horse-power, I did not put forward a similar recommendation relating to them. In this connection I would refer Mr. Poxon to a recent book by a French author.*

Replying to Dr. Rosenberg, in my view it is economic to make separate motors for $\frac{1}{8}$ and $\frac{1}{6}$ h.p. Even the small amount of material thus saved cannot by any means be disregarded. In general, the $\frac{1}{6}$-h.p. motor is of the same diameter as the $\frac{1}{4}$-h.p., but has a shorter core. It may be seen, however, that an accurate design method is essential to the engineer who is faced with the choice between adopting the above arrangement and using the $\frac{1}{8}$-h.p. diameter with a longer core.

I agree that my suggestions regarding the choice of slot combinations are not a complete solution to the problem, but, on the other hand, I do not think it fair to say that because a compromise may be necessary my method is no improvement on a guess.

I share Dr. Rosenberg's dislike of the term " super-silent," and for that reason I put it in inverted commas.

The factor of 70 % may be taken for motors over the range $\frac{1}{8}$ to $\frac{3}{4}$ h.p. at 1 500 r.p.m. (synchronous). Actually, perhaps over this range it should vary from 67 % to 73 %. I could not give a factor for the ratio between the copper and the slot area without first stipulating the slot insulation.

I am much obliged to Mr. Ritter for pointing out the error in the expressions in the Appendix. The brackets which he mentions should have been used.

The answer to Mr. Eley's first three questions is in the negative. I do not think it would be found possible or necessary to use double squirrel-cage rotors in f.h.p. motors, and I regret to say I have no experience with the process he mentions.

In reply to Dr. Parton, I feel that the synchronous motor, like many other types in which I am very interested, falls outside the scope of the paper.

I can assure Mr. Middleton that he will find competition difficult if he cannot get down to the dimensions indicated by expression (1).

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* N. F. T. SAUNDERS: " The Control of Speed and Torque of Squirrel-cage Motors," *Electrician*, 1933, vol. 111, p. 111.

* R. BEYAERT: " Les Petits Moteurs Électriques " (Dunod, Paris).

It is, of course, necessary to adopt resilient mounting to obtain a quiet motor, but in the paper I deliberately omitted all reference to questions of mechanical design.

It appears to me that Mr. Middleton has been unfortunate in his choice of impregnating varnish, and his method of using it in stators wound with enamelled wire. The solution of these problems is vital to the successful employment of this covering.

The relative difficulty of, on the one hand getting good joints in a copper rotor, and, on the other, of obtaining homogeneity in a cast aluminium rotor, is entirely of manufacturing interest; and I still think the advantage is with copper on theoretical grounds, simply because of its much lower specific resistance.

The method of calculating the rotor resistance, which is necessary to explain the factor of 0·64, was omitted for the sake of brevity. It is as follows: The length of the bar should be taken as the length in the slot plus the portions making contact with the end rings; or, where the bars are brazed to the rings, the length plus twice the width of the ring. The resistance of the bar is given by

$$r_b = \frac{0{\cdot}68 \times 10^{-6} l_b n_b}{a_b}$$

where l_b = length of bar, in inches; n_b = total number of bars; and a_b = cross-section of one bar, in square inches. The end-ring resistance is

$$r_r = \frac{0{\cdot}68 \times 10^{-6} \,.\, l_r \times 2}{a_r}$$

where l_r = mean length of one ring (i.e. the mean circumference of a ring); and a_r = cross-section of one ring, in square inches. The end-ring resistance is "referred" to the bar resistance thus:—

$$r_r^b = r_r \left(\frac{n_b}{2p\pi}\right)^2$$

The total rotor resistance is then

$$r_2^0 = r_b + r_r^b$$

The rotor resistance "referred" to the stator running winding is

$$r_2 = r_2^0 \left(\frac{2pq_1 z_1 F_D F_C F_P}{n_b F_{DR}}\right)^2$$

where F_D = distribution factor for the stator winding in question, F_P = factor depending on the number of phases for which the stator is wound, F_{DR} = distribution factor for the rotor winding, and F_C = chord factor. In the single-phase case, with a concentric winding, F_P and F_C are unity and F_{DR} is 0·64. In the 3-phase case, F_P is 3, F_{DR} is 0·95, and F_C is unity for concentric windings or is calculated as shown in Section (11) for other windings. When calculating the hot resistance, allowance should be made for the fact that the rotor usually gets hotter than the stator. In general, it may be taken that when the stator resistance is increased by 16 % (deg. C. rise), the rotor resistance should be increased by 20 %; and when the stator increase is 20 %, the rotor increase should be 25 %.

I have never been able to see the necessity or advantage in imagining that a single-phase motor has two fields rotating in opposite directions, when it quite obviously (to me) has no rotating field at all.

I must also disagree that the ratio of rotor diameter to core length does not vary very widely, and therefore that the factor mentioned is redundant.

If Mr. Middleton cares to calculate curves for the constants applicable to still smaller motors than those covered by mine, he will be doing a useful service from which I feel I am excused by my own labours.

The choice of a design sheet is, of course, very much a matter of taste and habit. I have no particular quarrel with the suggestion made, but would still prefer to use my own.

It will generally be found that the requirements of high starting torque for minimum condenser capacitance rule out any possibility of choosing a starting winding which will keep down the voltage across the condenser.

In reply to Mr. Blackledge, I would say that since the number of rotor bars is generally of the order of 50 % to 100 % more than the number of stator slots, and since it may not be easy or convenient to stipulate that the rotor skew shall be one stator slot pitch, I have often simply called for a skew of twice the rotor slot pitch.

In putting forward the expression (3) I expected some controversy, and the discussion has fully justified this expectation. I had no intention of suggesting that the expression was original, and it was because I was familiar with the work of many writers who have given either the same or a very similar expression that I refrained from attributing it to any particular author. I have always found great difficulty in deciding how much of the work referred to was the result of pure mathematical investigation, and for this reason I described the expression as "largely empirical." In this connection it is interesting to note that whereas Hildebrand gives the same expression, his recommendation regarding the use of it is the exact opposite of mine. I feel that Mr. Rawcliffe has made an excellent suggestion in rewriting the expression, and I agree that this simple modification represents a distinct improvement.

In very small motors, driving a definite load (for example, a desk fan), I have often taken advantage of the reduction in noise from no load to full load, due to the reduction in flux density.

With regard to the Table given by Mr. Blackledge, I think the explanation is that the factors used in the calculation of the magnetizing current cannot be divorced from the factors used in calculating the ampere-turns, and here again the confusion has arisen owing to the omission of the latter in the interests of brevity.

I heartily endorse the sentiments expressed by Mr. Butcher regarding American design. In general, American design in f.h.p. motors leads the whole world, although in fairness to our own people it should be stated that this is probably due to the much larger amounts of money and time which are placed at the disposal of American designers.

I agree with Dr. Kahn that the mechanical design of f.h.p. motors is quite as important as the electrical design, and for that reason I consider that it demands a separate paper.

It may be quite true that 90 % of the sales of Mr. Jack's company are of single-phase motors, but I would point out that the same figure does not necessarily apply to other manufacturers. Of course, it is quite easy to get the same output from a given motor on 3-phase, but I have often been instrumental in securing business by getting double the output on 3-phase as compared with the same machine wound for single-phase, and it is when this factor is borne in mind that my remarks assume importance.

Mr. Jack's remarks on the subject of cast aluminium rotors confirm my own views. No doubt his company, having purchased the necessary plant and experience, prefer, for manufacturing reasons, to use cast rotors; but this does not necessarily imply that another manufacturer who has achieved a corresponding degree of skill in producing copper rotors ought to jettison that experience.

I disagree that my argument in favour of 24 slots is unsound. Depending on the methods used in winding, it may be found cheaper to use 24 slots than 36, and if a distributed winding in 24 slots gives as good a result as a plain winding in 36 slots, but at a lower cost, then it is obviously right to use 24.

In reply to Dr. Pohl, I do not think that asbestos-covered wire can be used with advantage in f.h.p. motors, owing to the very poor winding factor obtainable with this covering.

I would recommend Mr. Cranston to use wire insulated with enamel and paper, or enamel and cotton, on 3-phase stators where the rating is to be not much higher than the single-phase rating; but where he wishes to get the maximum possible 3-phase output I see no objection to using enamelled wire. Surely, in a given frame the voltage between turns cannot be higher on 3-phase, and therefore the problem is purely one of insulation of the slot and between coils on the end winding.

The suggested method of core building might prove advantageous if it could be achieved in practice, but this would obviously necessitate some form of automatic stacking from the press.

The small capacitor start and run fan motors referred to by Mr. Mare do not employ static condensers, since these are only suitable for a brief duty cycle. I have already covered his queries regarding etched-foil condensers.

I do not think Mr. Henderson's fear of employing a current density of 60 000 amp. per sq. in. is justified. A temperature-rise at the rate of 4 or 5 deg. C. per sec. is not serious when it is considered that even on the heaviest loads found in practice (e.g. the compressor of a domestic refrigerator), the starting period is only of the order of 0·2 sec.

In Mr. Bottle and in Mr. Richardson I am afraid I have found designers who prefer graphical methods, and I can therefore do no more than congratulate Mr. Bottle on his circle diagram. I agree that it is unfortunate that the paper does not deal more fully with the capacitor motor and that it neglects the shaded-pole motor, but it was impossible to deal adequately with these within the confines of a single paper.

I sympathize with Mr. Joseph in his unfortunate experiences with centrifugal switches; but I assure him it is possible to buy motors in which this particular component is as reliable as the remainder of the motor. A Twinob switch is certainly very useful, but unfortunately it cannot be employed in conjunction with automatic starting; and I would not recommend it for domestic use.

I cannot quite understand Mr. Kerr's remarks on the relationship between heating and exposed stampings. From the point of view of temperature-rise, both internal and external, I would favour the machine with a shell. I entirely agree with him in stressing the desirability of low temperature-rises in f.h.p. motors.

I would explain to Prof. Cramp that I had no intention of claiming as original, devices which are quite old, nor do I think I did so. It is impossible in a paper of this description to give chapter and verse for everything, and in any case, when one considers how rarely designers publish their methods, it is not surprising if several of them discover the same thing simultaneously.

Some years ago I experimented with the type of motor described by Prof. Cramp, but I came to the conclusion that the principle could not be usefully employed in f.h.p. motors, owing to the difficulty (in the small dimensions available) of regulating satisfactorily the reactance of the squirrel cage. In addition, the cost of the armature of such a machine is considerably more than the total cost of the squirrel-cage rotor plus the condenser of a capacitor motor giving a superior performance, and the cost of the brushgear and brushes is higher than that of a centrifugal switch.

I would recommend Mr. Manighetti to seek advice from the manufacturers of enamelled wire. Undoubtedly the successful use of this material depends largely on using correct impregnating methods and materials.

I regret, also, that I feel unable to deal with Mr. Philpott's questions on problems in the manufacture of cast aluminium rotors.

In my view a centrifugal switch is cheaper than a magnetic switch of equal quality. While there is no doubt that a magnetic switch can be completely enclosed for protection against atmospheric conditions, it will be found that this, together with satisfactory action and freedom from noise due to vibration of the magnet core, involves a prohibitive cost.

THE CALIBRATION OF FOUR-AERIAL ADCOCK DIRECTION-FINDERS*

By W. ROSS, M.A.

(*Paper first received* 31*st October, and in revised form* 19*th December*, 1938; *read before the* WIRELESS SECTION 1*st March*, 1939.)

SUMMARY

The paper describes how it is possible to determine the minimum radius at which a four-aerial Adcock direction-finder may be calibrated for instrumental error without introducing spurious effects due to the proximity of the calibrating transmitter to the direction-finder. It is shown that this minimum radius depends upon the spacing of the aerials, the wavelength, and the inherent accuracy of the direction-finder to be calibrated. In most cases of practical interest the minimum radius is found to be between $0\cdot 6\,\lambda$ and $3\cdot 5\,\lambda$. Such distances, while usually easily attainable on the short wave band, may not be possible in the case of medium or long wavelengths.

INTRODUCTION

In the operation of radio direction-finding the user is generally faced with the problem of effecting the best possible calibration of his instrument which circumstances permit. Ideally, an overall calibration would be made by setting up a transmitter at known points in the sector and at the distances for which the direction-finder is required to be used.

In practice this may not always be possible, and the expedient of using calibrations made at one particular distance for tranmissions from all distances is quite often prone to lead to errors. Part at least of the error revealed by such a calibration (e.g. error arising from changes in the medium in which or over which propagation takes place) is frequently found to vary considerably with distance. That part of the error arising in the instrument itself is, however, a constant, and, if known, could always be allowed for accurately. Indeed, in cases where an ideal overall calibration is not possible it may often be best to allow only for the known instrumental error rather than apply some other calibration not known to apply to the particular range in question; while in cases where no other calibration at all is possible it is desirable at least to allow for the instrumental error, and to have a means of checking the constancy of calibration of the instrument when desired.

The object of this paper is to show that in most cases it is possible to separate the instrumental error from other errors which arise, and to perform a calibration which gives directly the instrumental error.

DETERMINATION OF INSTRUMENTAL ERROR

It has been shown in another paper† how the maximum value of the instrumental error of a four-aerial direction-finder may be determined by the use of an oscillator placed at the centre of the system. The method there described does not enable a calibration of the instrument to be made but is simply a means of determining the overall accuracy of the instrument. The present paper is concerned essentially with the actual calibration of a direction-finder for instrumental error.

If a direction-finder were located alone on an infinite uniform plane, in circumstances in which the effects of any ionospheric regions were either negligible or non-existent, calibration at any radius sufficiently great would provide a curve of instrumental error, since in this case no question of site or path error would arise. In practice, of course, direction-finders are not so situated, and at some radius the properties of the site begin to change or obstacles appear in the field between transmitter and direction-finder. Once this radius is reached, it will generally be found that calibrations at successive radii do not agree with any precision. In other words, various path and site errors begin to appear. Usually, however, the site of the direction-finder resembles the ideal infinite uniform plane up to some radius and, providing this radius is sufficiently great, calibrations made within it will give the instrumental error of the apparatus. For this to be true it is necessary that the " uniform " portion of the site be sufficiently large to enable a portable transmitter to be carried round the direction-finder at a radius great enough to eliminate spurious errors of the kind dealt with later in this paper, due to too close proximity between the direction-finder and the transmitter, and yet not so great that the transmitter comes close to the boundary of the " uniform " part of the site. Beyond this boundary will usually be found undesirable obstacles of various kinds such as trees, buildings, telegraph wires, railways, metal pylons or poles, and other objects which, if close to the calibrating transmitter, would give rise to errors which were neither instrumental nor yet true site errors. It is therefore important to keep the calibrating transmitter well within the boundary of the uniform portion of the site if possible. At too close ranges, however, spurious errors again arise due to the fact that the field from the calibrating transmitter is not then equal at all four aerials of the Adcock direction-finder. The aim of this paper is to show what is the closest range at which calibration may be carried out so as to be free from such " proximity " errors. Since, in practice, the uniform portion of the site is usually limited, it will be best to carry out the instrumental calibration at as close range to the direction-finder as is permissible. Hence the necessity for determining the minimum possible calibrating distance.

ERRORS DUE TO PROXIMITY OF CALIBRATING TRANSMITTER

Errors due to proximity of the calibrating transmitter to the direction-finder arise, as has been said, from the inequality of field strength at the four aerials of the direction-finder.

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* Official communication from the National Physical Laboratory.
This paper was included in the Symposium of papers on Direction-Finding read before the Wireless Section on the 1st March, 1939 (see page 203).
† See Reference (1).

It is assumed throughout the paper that the aerials of the direction-finder and of the calibrating oscillator are sufficiently short, so that the value of the electric field may be assumed to be constant over any single aerial of the direction-finder. Since, in practice, the aerials of an Adcock direction-finder are generally short compared with the wavelength, and since, as will be shown later, the minimum radius at which calibration may be made is of the order of one or two wavelengths, the error introduced by making this assumption is inappreciable. It is further assumed that the effects of ground attenuation are negligible over distances of the order of a wavelength. The expression for the field from a small vertical radiator is then a relatively simple function of distance. The expression contains terms which vary inversely as the distance, distance squared, and distance cubed, and when the calibrating radius is small compared with either the wavelength or the spacing between the aerials, the difference of field strength at the various aerials may be appreciable.

It will be shown later in the paper how some allowance can be made for the effects of ground attenuation if this is known to be appreciable.

There are two effects due to proximity which differ in nature and are most conveniently dealt with separately. In the first place, the difference in field strength at the aerials gives rise to errors in itself, errors which would appear however perfect the direction-finder, and which disappear when the distance of the transmitter is great enough. In the second place, the difference in field strength at the four aerials modifies the effects of the slight differences which always exist amongst the aerials of a direction-finder and give rise to part at least of the instrumental error. This modification of the effect of the slight unbalances existing amongst the aerials means that a true value of the instrumental error is not arrived at when the transmitter is too close.

ADDITIONAL ERRORS DUE TO PROXIMITY

We shall consider in this section the first type of "proximity" effect referred to above, namely the additional errors introduced by proximity.

Referring to Fig. 1, A, B, C, and D are the four aerials of the Adcock direction-finder, O is the centre of the aerial system, and P is the calibrating oscillator. ϕ is the azimuth of the transmitter relative to the direction OA. We shall call OP the distance of the transmitter and refer to it as r. The spacing of the aerials AB or CD we shall call s.

Let E_1, E_2, E_3, and E_4 be the amplitude of either the inverse distance, inverse-square, or inverse-cube terms in the expression for the field strength from P at A, B, C, and D respectively. It can easily be shown (see Appendix I) that the resultant e.m.f. in the pair AB due to any one of the terms is proportional to

$$(E_1 + E_2)\frac{\pi s \cos\phi}{\lambda} \cos\omega t + (E_1 - E_2) \sin\omega t$$

and in the pair CD to

$$(E_3 + E_4)\frac{\pi s \sin\phi}{\lambda} \cos\omega t + (E_3 - E_4) \sin\omega t$$

where it is assumed that s/λ is so small that $\sin \pi s/\lambda = \pi s/\lambda$ with sufficient accuracy, ωt is the phase of the field at O (approximately), and $\omega = 2\pi \times$ frequency of the wave.

Since the field strength contains inverse-distance, inverse-distance-squared, and inverse-distance-cubed terms, it is cumbersome to consider the effect of the general expression for field strength all at once. A simpler method and one that gives more readily interpretable results is to consider separately the effects of the inverse-distance, inverse-square, and inverse-cube terms. Thus in many cases it may turn out that the minimum radius specified by the inverse-distance term is so great that the other terms may be neglected in comparison with the inverse-distance term and the analysis greatly simplified. This method of treating separately the three terms will be followed throughout this paper without further reference to the reasons for so doing.

The method of combining the results for the separate terms to obtain the general result will be dealt with later in the paper.

Assuming then, first, that the field varies inversely as the distance, we obtain the following results (see Appendix II):—

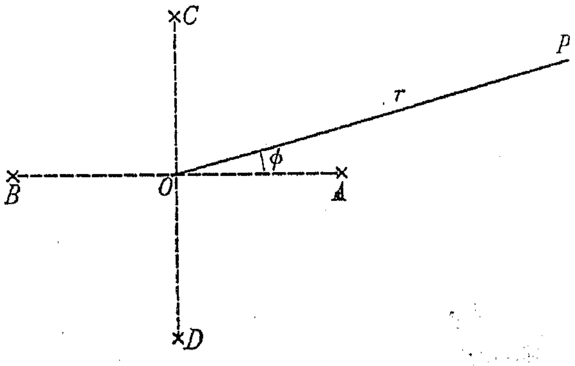

Fig. 1

$$\text{E.M.F. in pair AB} \propto \frac{1}{r}\left\{\left[2 - \frac{s^2}{4r^2}(1 - 3\cos^2\phi)\right] \frac{\pi s \cos\phi}{\lambda}\cos\omega t + \frac{s}{r}\cos\phi \sin\omega t\right\} \quad . \quad (1)$$

$$\text{E.M.F. in pair CD} \propto \frac{1}{r}\left\{\left[2 - \frac{s^2}{4r^2}(1 - 3\sin^2\phi)\right] \frac{\pi s \sin\phi}{\lambda}\cos\omega t + \frac{s}{r}\sin\phi \sin\omega t\right\} \quad . \quad (2)$$

These expressions are accurate up to and including terms of the order of s^2/r^2.

By inspection we note that the e.m.f.'s are not exactly in phase, nor is their ratio exactly equal to $\tan\phi$ as would be the case if r were very great. To a first approximation the phase difference introduced will not affect the bearing obtained, as has been shown in another paper.* As we are only concerned with first-order effects produced by proximity (since it is the object of the paper to show when first-order effects will themselves be small), it is sufficient to take it that the bearing which will be obtained will be ϕ', where

$$\tan\phi' = \frac{\text{E.M.F. in pair CD}}{\text{E.M.F. in pair AB}}$$

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* See Reference (1).

From this result and equations (1) and (2) we can deduce that the error in bearing $(\phi' - \phi)$ is given by (see Appendix III):—

$$\tan(\phi' - \phi) = -\frac{3}{32}\frac{s^2}{r^2 + (\lambda^2/4\pi^2)}\sin 4\phi$$

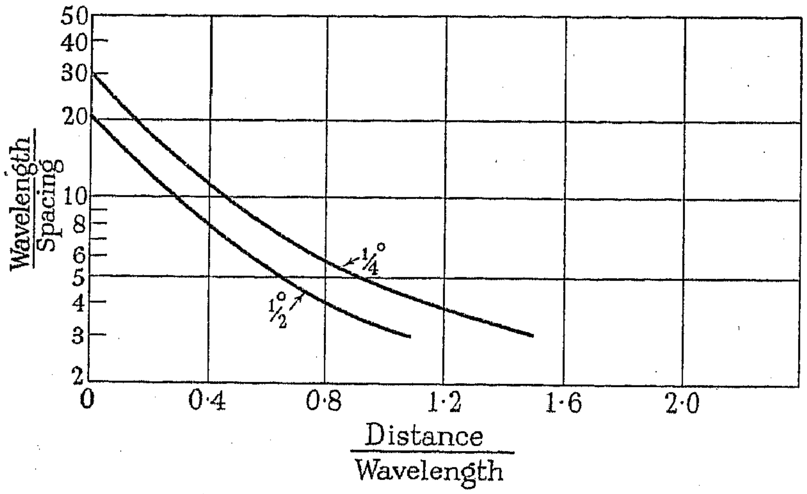

Fig. 2.—Inverse distance law of attenuation of field strength. Curves showing minimum value of ratio Distance/Wavelength so that maximum additional error introduced does not exceed ½° or ¼°.

(The error to which these curves refer would appear even with a perfect Adcock direction-finder.)

i.e. the error is octantal and has a maximum value given approximately by

$$\phi' - \phi = \frac{3}{32}\frac{s^2}{r^2 + (\lambda^2/4\pi^2)} \quad . \quad . \quad . \quad (3)$$

Similar analysis gives, for an inverse square law of force,

$$\phi' - \phi = \frac{1}{4}\frac{s^2}{r^2 + (\lambda^2/\pi^2)} \quad . \quad . \quad . \quad (4)$$

and, for an inverse cube law,

$$\phi' - \phi = \frac{15}{32}\frac{s^2}{r^2 + (9\lambda^2/4\pi^2)} \quad . \quad . \quad . \quad (5)$$

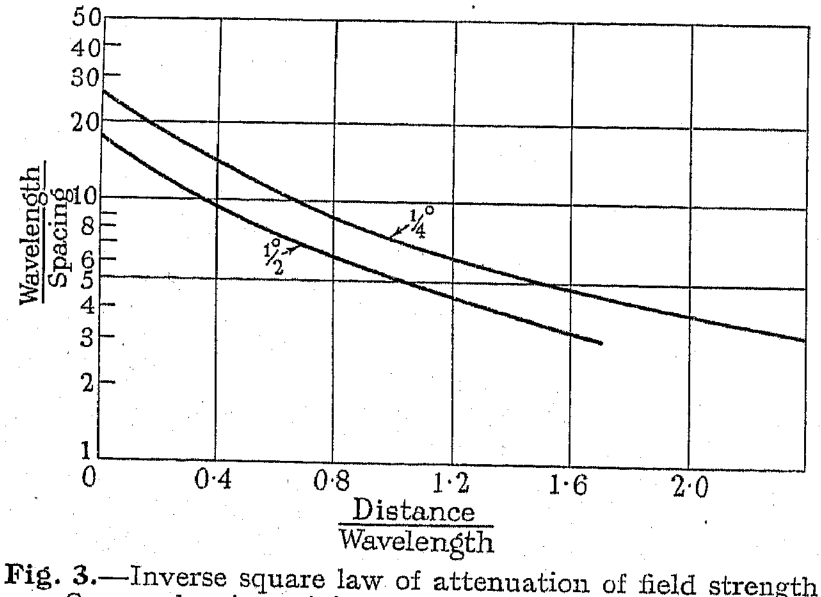

Fig. 3.—Inverse square law of attenuation of field strength. Curves showing minimum value of ratio Distance/Wavelength so that maximum additional error introduced does not exceed ½° or ¼°.

(The error to which these curves refer would appear even with a perfect Adcock direction-finder.)

Curves have been constructed from (3) and (4), showing the minimum radius (as a function of wavelength) for which the error shall not exceed ½° or ¼° in the two cases of an inverse-distance and inverse-square law of force (see Figs. 2 and 3).

MODIFICATION OF EXISTING INSTRUMENTAL ERRORS BY PROXIMITY OF CALIBRATING OSCILLATOR

We shall consider in this section the modifications which will be produced in existing instrumental errors by proximity of the calibrating oscillator. There are several types of errors likely to be affected, and these are dealt with separately below.

(a) Errors due to Phase Unbalance between the Two Members of any Pair of Aerials

Suppose that in the pair CD there exists a spurious phase-difference between the e.m.f.'s in aerials of amount ψ due to mismatching of the aerials. With a distant transmitter this will produce a maximum bearing error given by

$$\epsilon_{max} = \frac{\psi}{2\pi s/\lambda} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

as has been shown elsewhere.[*]

Let us assume that the phase error ψ arises in the aerial C, i.e. the phase relation between the current in the aerial and the inducing electromagnetic field is the same for aerials A, B, and D, but in the case of C differs by ψ from that for the other aerials.

It can be shown (see Appendix IV) that the amplitude of the e.m.f. in the pair CD is now given by

$$Q = \left[(E_3 + E_4)^2\frac{\pi^2 s^2 \sin^2\phi}{\lambda^2} + (E_3 - E_4)^2\right]^{\frac{1}{2}}$$
$$\left[1 + \frac{E_3\psi(E_3 + E_4)\dfrac{\pi s \sin\phi}{\lambda}}{(E_3 + E_4)^2\dfrac{\pi^2 s^2 \sin^2\phi}{\lambda^2} + (E_3 - E_4)^2}\right]$$

which can be written

$$Q = Q_0[1 + \Delta']$$

where Δ' is the amplitude error in the e.m.f. in CD introduced by ψ, and Q_0 is the value of Q when $\psi = 0$.

Now it has been shown[†] that when there is an amplitude error Δ' in the value of the e.m.f. in one aerial pair relative to the other aerial pair, an error ϵ' is produced such that

$$\epsilon' = \frac{\Delta' \sin 2\phi}{2}$$

Let Δ be the value of Δ' when r becomes very great. Since

$$\Delta' = \frac{E_3\psi(E_3 + E_4)\dfrac{\pi s \sin\phi}{\lambda}}{(E_3 + E_4)^2\dfrac{\pi^2 s^2 \sin^2\phi}{\lambda^2} + (E_3 - E_4)^2}$$

it is seen that, since when $r \rightarrow \infty$ $E_3 = E_4$,

$$\Delta = \frac{\psi}{(2\pi s/\lambda)\sin\phi}$$

Let ϵ be the corresponding value of ϵ' when r is great. Then

$$\epsilon = \frac{\Delta \sin 2\phi}{2}$$

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[*] See Reference (1).

[†] *Ibid.*

ϵ is the true value of the instrumental error due to phase misbalance ψ between aerials C and D, and ϵ' is the spurious value of ϵ obtained by too close-range calibration. We must choose a value of r such that $(\epsilon' - \epsilon)$ is as small as we may require.

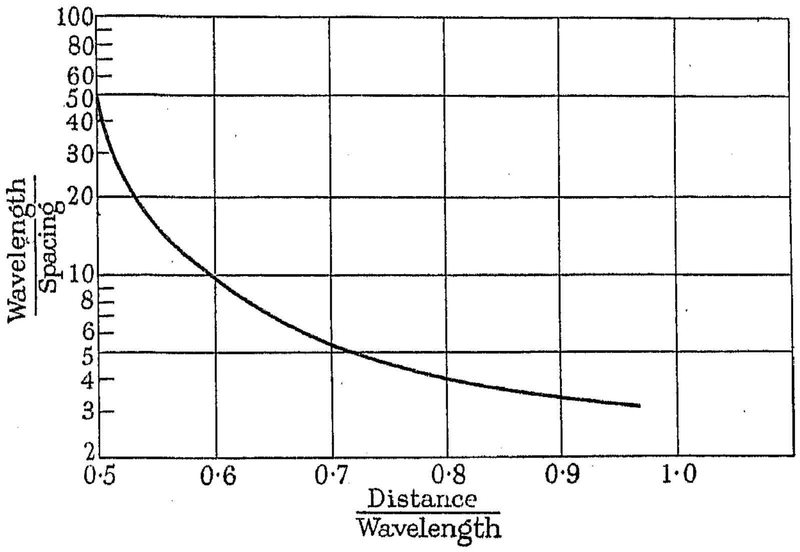

Fig. 4.—Inverse distance law. Curves showing minimum distance so that the modification of the instrumental error due to proximity effect (that is, $\epsilon - \epsilon'$) does not exceed $\frac{1}{10}\epsilon_{max}$.

It is fairly easily deduced that (see Appendix V)

$$\epsilon - \epsilon' = \epsilon_{max}\left(1 - \frac{\Delta'}{\Delta}\right)\cos\phi$$

where ϵ_{max} is the maximum value of ϵ, viz. $\psi \Big/ \frac{2\pi s}{\lambda}$.

Assuming once more the three possible laws of variation of field strength, we get the results (see Appendix VI):—

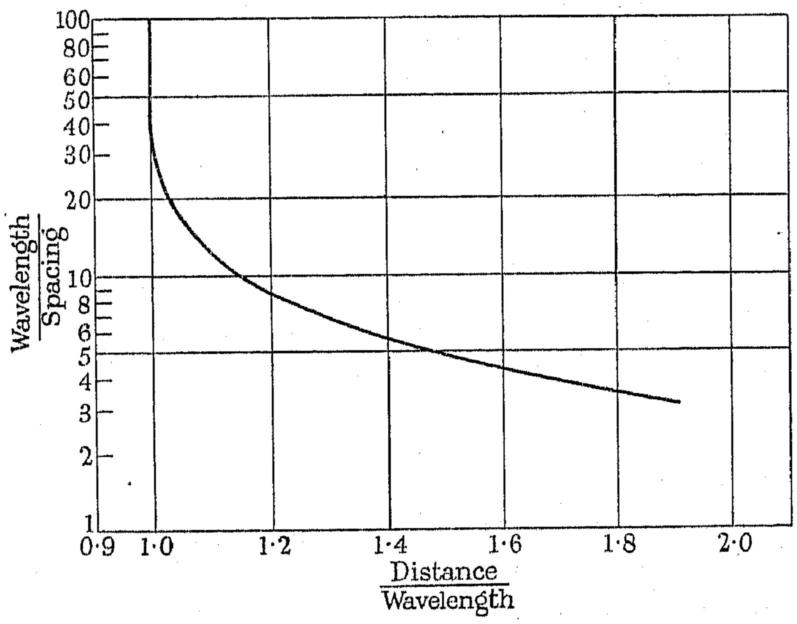

Fig. 5.—Inverse square law.

Curves showing minimum distance so that the modification of the instrumental error due to proximity effect (that is, $\epsilon - \epsilon'$) does not exceed $\frac{1}{10}\epsilon_{max}$.

Inverse distance law

$$\epsilon - \epsilon' = \epsilon_{max}\cos\phi\left(\frac{\lambda^2}{4\pi^2 r^2} - \frac{s}{2r}\sin\phi\right) \quad . \quad . \quad (7)$$

Inverse distance-squared law

$$\epsilon - \epsilon' = \epsilon_{max}\cos\phi\left(\frac{\lambda^2}{\pi^2 r^2} - \frac{s}{r}\sin\phi\right) \quad . \quad . \quad . \quad (8)$$

Inverse distance-cubed law

$$\epsilon - \epsilon' = \epsilon_{max}\cos\phi\left(\frac{9\lambda^2}{4\pi^2 r^2} - \frac{3s}{2r}\sin\phi\right) \quad . \quad . \quad (9)$$

Examination of equations (7) to (9) reveals that the value of ϕ at which $(\epsilon - \epsilon')$ reaches its maximum varies with the distance r. It can be easily shown (see Appendix VII) that the value of ϕ for a maximum is given by

$$\sin\phi = \frac{\frac{\lambda^2}{4\pi^2 r^2} - \sqrt{\left(\frac{\lambda^4}{16\pi^4 r^4} + 2\frac{s^2}{r^2}\right)}}{2s/r}$$

in the case of the inverse distance law. Similar expressions can be deduced for the other two laws.

In order to present the results of these equations in their most useful form, Figs. 4 and 5 have been constructed showing the minimum radius (as a function of wavelength) for which $(\epsilon - \epsilon')$ at its maximum does not exceed $\frac{1}{10}\epsilon_{max}$. Curves are given only for the inverse-distance and inverse-square laws. It is assumed that in any well-designed Adcock system ϵ_{max} will be so small that $\frac{1}{10}\epsilon_{max}$ is negligible.

(b) Errors due to Amplitude Unbalance between the Two Members of any Pair of Aerials

A difference in amplitude between the currents induced in two aerials of an Adcock pair when exposed to the same field gives rise to a signal practically 90° out of phase with the main signal in the pair, thus producing mainly a flattening of the bearing with practically no bearing error.*

Thus, suppose aerials A, B, and D have signal amplitudes proportional to unity, while aerial C has signal amplitude proportional to $(1 + \delta)$. The resulting magnetic field in the goniometer will be elliptical and will have a maximum ratio of minor to major axis (k_{max}) given by†

$$k_{max} = \frac{\delta}{2\pi s/\lambda} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

in the case of a distant transmitter.

The amplitude error of the e.m.f. in the pair CD relative to the pair AB is $\delta/2$ in the case of a distant transmitter which produces a bearing error of maximum value $\delta/4$, which is usually small compared with the ellipsing if s/λ is small.

Coming now to the case of a transmitter at close range, we have, for the e.m.f. in limb CD,

$$[E_3(1 + \delta) + E_4]\frac{\pi s \sin\phi}{\lambda}\cos\omega t + [E_3(1 + \delta) - E_4]\sin\omega t$$

If Q is the amplitude of this e.m.f., then we have, for the inverse-distance law of force (see Appendix VIII),

$$r^2Q^2 = \frac{4\pi^2 s^2 \sin^2\phi}{\lambda^2}\left[1 - \frac{s^2}{4r^2}(1 - 3\sin^2\phi) + \delta\right] + \left[\frac{s^2\sin^2\phi}{r^2} + \frac{2\delta s\sin\phi}{r} + \delta^2\right]$$

(In the first bracket it is necessary to go only to terms of the first power of δ, but in the second we require to go to δ^2 since $\sin\phi$ may be zero, in which case δ^2 is the first significant term.)

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* See Reference (1).

† *Ibid.*

For convenience we shall write

$$\frac{4\pi^2 s^2 \sin^2\phi}{\lambda^2} = U^2$$

We can now write

$$rQ = rQ_0(1 + \Delta')$$

where (see Appendix IX)

$$\Delta' = \frac{\delta}{2}\left(1 + \frac{2s\sin\phi}{rU^2}\right)\left[1 + \frac{s^2}{4r^2}(1 - 3\sin^2\phi) - \frac{\lambda^2}{4\pi^2 r^2}\right] + \frac{\delta^2}{2U^2}\left[1 + \frac{s^2}{4r^2}(1 - 3\sin^2\phi) - \frac{\lambda^2}{4\pi^2 r^2}\right] \quad . \quad (11)$$

and Q_0 = value of Q when $\delta = 0$.

Now except in the neighbourhood of $U = 0$, i.e. $\phi = 0$, we can write, with sufficient accuracy,

$$\Delta' = \frac{\delta}{2}\left(1 + \frac{2s\sin\phi}{rU^2}\right) \quad . \quad . \quad . \quad (12)$$

(We shall deal separately with the case where ϕ is nearly zero.)

We now note that as $r \to \infty$, $\Delta' \to \delta/2$, as was stated above to be the case for a distant transmitter. Write $\Delta = \delta/2$; then the additional error introduced by the proximity of the transmitter is given by (see Appendix X)

$$\eta' - \eta = \frac{(\Delta' - \Delta)}{2}\sin 2\phi$$

$$= \frac{\delta s \sin\phi\lambda^2}{r \,.\, 4\pi^2 s^2 \sin^2\phi}\sin\phi\cos\phi$$

$$\eta' - \eta = \delta \cdot \frac{\lambda}{2\pi r} \cdot \frac{\lambda}{2\pi s}\cos\phi \quad . \quad . \quad . \quad (13)$$

where η' is the error on the nearby transmitter, and η the error on a distant transmitter, due to the amplitude unbalance between aerials C and D.

This formula indicates that $(\eta' - \eta)$ is a maximum at $\phi = 0$, when it has the value

$$\delta \cdot \frac{\lambda}{2\pi r} \cdot \frac{\lambda}{2\pi s}$$

but the above analysis does not hold near $\phi = 0$.

Let us examine separately the case for which $\phi = 0$. If P = amplitude of e.m.f. in limb AB, and Q = e.m.f. in CD (Fig. 1), and α = phase difference between these e.m.f.'s, then the inclination of the major axis of the elliptical field in the goniometer relative to the datum axis (i.e. the bearing) is given by θ, where

$$\tan 2\theta = \frac{2PQ}{P^2 - Q^2}\cos\alpha$$

(This follows from the geometry of the ellipse.)

Consider now the case of a nearby transmitter and assume the inverse-distance law of variation of electric force. Let us calculate P, Q, and α for the case in which $\phi = 0$ and the aerial C has amplitude unbalance δ relative to the other aerials.

$$\text{E.M.F. in AB} \propto \frac{1}{r}\left(2 + \frac{2s^2}{4r^2}\right)\frac{\pi s}{\lambda}\cos\omega t + \frac{1}{r}\frac{s}{r}\sin\omega t$$

(see equation 1)

$$\text{E.M.F. in CD} \propto \frac{\delta}{r}\sin\omega t$$

The phase difference α is such that

$$\tan\alpha = \frac{\left(2 + \frac{s^2}{2r^2}\right)\frac{\pi s}{\lambda}}{s/r}$$

Assuming now that δ is small compared with $\pi s/\lambda$, we know that θ will be somewhere in the neighbourhood of zero; so for the equation

$$\tan 2\theta = \frac{2PQ}{P^2 - Q^2}\cos\alpha$$

we can write approximately

$$2\theta = \frac{2PQ}{P^2 - Q^2}\cos\alpha$$

$$= \frac{2Q}{P}\cos\alpha \quad \text{(since } Q \text{ is assumed small compared with } P\text{)}$$

That is, $\theta = \dfrac{Q}{P}\cos\alpha$

Hence

$$\theta = \frac{\delta}{\sqrt{\left[\left(2 + \frac{s^2}{2r^2}\right)^2\frac{\pi^2 s^2}{\lambda^2} + \frac{s^2}{r^2}\right]}} \times \frac{s/r}{\sqrt{\left[\left(2 + \frac{s^2}{2r^2}\right)^2\frac{\pi^2 s^2}{\lambda^2} + \frac{s^2}{r^2}\right]}}$$

$$= \frac{\delta \,.\, \frac{s}{r}}{\frac{4\pi^2 s^2}{\lambda^2}} \quad \text{with sufficient accuracy}$$

$$= \delta \cdot \frac{\lambda}{2\pi r} \cdot \frac{\lambda}{2\pi s}$$

i.e. θ has the value to which the expression (13) tends as ϕ tends to zero. Expression (13) therefore gives the value of $(\eta' - \eta)$ for all values of ϕ. We see, therefore, that the maximum value of $(\eta' - \eta)$ is given by

$$\delta \cdot \frac{\lambda}{2\pi r} \cdot \frac{\lambda}{2\pi s}$$

Comparing this with equation (9), we see that

$$(\eta' - \eta)_{max} = \frac{\lambda}{2\pi r}k_{max} \quad . \quad . \quad . \quad (14)$$

i.e. $(\eta' - \eta)_{max}$ equals $\lambda/(2\pi r)$ times the maximum value of the ellipticity produced on bearings from a distant transmitter by the amplitude unbalance of aerials C and D.

The inverse square law gives

$$(\eta' - \eta)_{max} = \frac{\lambda}{\pi r} \times k_{max} \quad . \quad . \quad . \quad (15)$$

and the inverse cube law gives

$$(\eta' - \eta)_{max} = \frac{3\lambda}{2\pi r}k_{max} \quad . \quad . \quad . \quad (16)$$

Now normally it may not be possible to observe k_{max} directly, particularly in the case of an aural direction-finder, but it is safe to assume that k_{max} (expressed as a ratio, see equation **10**) will have about the same value as ϵ_{max} (expressed in radians, see equation **6**). This means that, in general, when the aerials in a direction-finder are not perfectly balanced with respect to each other, the phase and amplitude unbalances will be of the same order.

(c) Errors due to Phase or Amplitude Differences of One Pair of Aerials relative to the Other Pair

It is clear that in this case the relative phase or amplitude errors persist unchanged whatever the distance of the transmitter. For example, suppose the aerials in pair CD have a pick-up equal to $(1 + \Delta)$ times the pick-up of aerials in pair AB for a distant transmitter; then when the transmitter is brought close to the direction-finder the pick-up of pair CD is still $(1 + \Delta)$ times what it would be if aerials C and D had identical pick-up with A and B.

COMBINATION OF RESULTS FOR THE THREE TERMS IN THE GENERAL EXPRESSION FOR FIELD STRENGTH

In practice, when the transmitter is close to the direction-finder it is necessary to take account of three terms in the expression for the field strength, these terms being inversely proportional to distance, distance squared, and distance cubed respectively. It may be noted that the three terms are equal in magnitude at a distance of $\lambda/(2\pi)$.

Now if two waves (of the same frequency and of relative amplitude $1 : x$) arrive at a direction-finder at an angular separation (real or apparent) equal to ρ (in azimuth) and a phase difference of 90°, the angle between the resultant bearing and the bearing given by the greater of the two alone is σ, where*

$$\sigma = \rho\frac{x^2}{1 + x^2}$$

For example, if $x = \frac{1}{3}$, $\sigma = \frac{1}{10}\rho$ approximately

and if $x = \frac{1}{10}$, $\sigma = \frac{1}{100}\rho$ approximately.

The inverse-square term is 90° out of phase with the inverse-distance term, and the inverse-cube term is 180° out of phase with the latter.

When now it is desired to take account of all three fields in determining the proximity effect, the first operation is to determine the proximity errors for the three fields separately, at the particular radius chosen. Next determine the relative amplitudes of the three fields. Usually, it will be found at this stage that the inverse cube term is entirely negligible, and for this reason curves relating to it alone have generally been omitted from this paper.

Assuming that the other two terms are comparable, however (e.g. at a distance of $\lambda/2$ the inverse square term is approximately one-third of the inverse distance term), the next operation is to determine ρ, the difference in the proximity errors for the two fields taken separately. From this, determine

$$\sigma = \rho\frac{x^2}{1 + x^2}$$

where x is the ratio of amplitudes of the two fields $(x < 1)$. For the case cited above we shall obtain $\sigma = \frac{1}{10}\rho$. Usually this will be entirely negligible and we can determine the " proximity " error from considerations of the inverse distance field alone, for by neglecting the inverse square field we are neglecting a fraction of the proximity error of maximum value

$$\sigma = \frac{\rho x^2}{1 + x^2}$$

PRACTICAL APPLICATION OF RESULTS

We come now to the application of the above analysis to the practical case of calibrating a direction-finder for instrumental error. If the results arrived at in the previous sections are studied it will be noted that the minimum radius possible for the determination of the instrumental error with a prescribed degree of accuracy (e.g. to within ¼° or ½°, as the case may be) depends upon the inherent accuracy of the Adcock system to be calibrated. This is so since the additional " proximity " errors introduced depend upon ϵ_{max} and k_{max} for a distant transmitter, as shown above. For example, if $\epsilon_{max} = 2\frac{1}{2}°$ and we wish to perform the instrumental calibration with an accuracy of ½°, we must choose a radius such that

$$\epsilon - \epsilon' \leqslant \tfrac{1}{10}\epsilon_{max}$$

but if $\epsilon_{max} = 10°$ we have to choose a radius such that

$$\epsilon - \epsilon' \leqslant \tfrac{1}{40}\epsilon_{max}$$

In deciding what is the minimum possible calibrating radius it is therefore necessary to know at least the order of magnitude of ϵ_{max} and k_{max}.

If it is possible to make measurements of the aerial balance by the methods involving the use of a centrally placed oscillator, described in a previous paper by R. H. Barfield and the author,* ϵ_{max} and k_{max} may be determined from these balance measurements. This will usually not be possible, but ϵ_{max} and k_{max} may still be obtained with sufficient accuracy for the purpose of determining the minimum calibrating radius, as follows.

A small transmitter is placed successively at the four points on the lines joining the aerials produced (i.e. normally due north, south, east, and west of the direction-finder). As great a radius as possible within the confines of the site, and up to about one wavelength, should be chosen for this purpose. At each point the bearing error and ellipticity are observed, the latter being obtained in the case of an aural system as the ratio of the signal at minimum to the signal at maximum if it is possible to measure this ratio. The ellipticity is observed directly in the case of a cathode-ray direction-finder. If it is not possible to determine the ellipticity directly for any reason (e.g. non-linearity of output of receiver), it is usually safe to assume it to have about the same value as the bearing error (expressed in radians).

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* See Reference (2).

* See Reference (1).

Now if the errors obtained in this test are purely instrumental errors it should be found that the error on a transmitter due north of the direction-finder has the same absolute value as the error on a transmitter due south. The same applies to errors due east and due west. (This assumes the aerial system is laid out with aerials north, south, east, and west, of course). If this is not so it means that some site or path error is also making itself apparent. Suppose ϵ_1 is the mean of the errors for a transmitter due north and due south, and ϵ_2 the mean of the errors for a transmitter due east and west. Let k_1 and k_2 be the corresponding mean ellipticities. Then the best values to take for ϵ_{max} and k_{max} are given by

$$\epsilon_{max} = \sqrt{(\epsilon_1^2 + \epsilon_2^2)}$$

$$k_{max} = \sqrt{(k_1^2 + k_2^2)}$$

If the errors for a transmitter due north and due south are very nearly equal and the errors due east and west are also nearly equal, these expressions will give ϵ_{max} and k_{max} fairly accurately, but in any case they will give them with sufficient accuracy for the purpose of deciding upon the minimum permissible calibrating radius. Having obtained ϵ_{max} and k_{max}, we proceed as follows:—

(1) From the curve given in Fig. 2 determine r such that the additional octantal proximity error is not greater than the desired degree of accuracy of calibration.

(2) Knowing ϵ_{max} approximately, determine from the curve in Fig. 4, or from equation (7), the minimum radius, such that the additional instrumental error due to proximity from this source shall not exceed the prescribed degree of accuracy.

(3) Knowing (or assuming) an approximate value for k_{max}, determine from equation (14) a distance such that the additional proximity error from this source shall not exceed the prescribed accuracy.

Three radii will have been determined. Choose a radius slightly greater than the greatest of these three (the latter two will generally be greater than the first), and from it determine what value all three proximity errors have at this radius. Assume them to be additive and hence determine whether or not a great enough radius has been chosen. If not, repeat the calculation for a somewhat greater radius, bearing in mind that one of the proximity errors (that depending on k_{max}) varies inversely as the distance while the others vary approximately as the inverse square of the distance.

If the radius finally arrived at is very much greater than the radius used initially in the rough determination of ϵ_{max} and k_{max}, it will be necessary to re-determine these quantities at this greater radius and correct the calculations accordingly.

Finally, it is necessary to check that the omission of the inverse square term from the calculations is permissible by calculating the proximity error at the radius arrived at on the assumption of an inverse square law of force, and from equation (17) to decide whether this term adds appreciably to the error. Usually it will be found that the effect of this term can be entirely neglected, as can that of the inverse cube term.

This may seem a lengthy and rather untidy method, but the necessity of an iterative method is obvious from the complexity of the effects dealt with. To simplify the application of these results to practical cases, this rather tiresome process of calculation has been carried out for several special cases likely to be met with most frequently. The results of these calculations are presented in Figs. 6 and 7. These give the minimum calibrating radius as a function of wavelength, for various aerial spacings (also as a function of wavelength), for cases in which $\epsilon_{max} = 2\cdot5^\circ$ ($\frac{1}{23}$ radian) and $k_{max} = \frac{1}{23}$ approximately, and the required calibrating accuracy is $\frac{1}{2}^\circ$ or $\frac{1}{4}^\circ$. Figs. 6 and 7 also cover the case in which $\epsilon_{max} = 1\cdot25^\circ$ ($\frac{1}{46}$ radian) and $k_{max} = \frac{1}{46}$, and the required calibrating accuracy is $\frac{1}{2}^\circ$ or $\frac{1}{4}^\circ$.

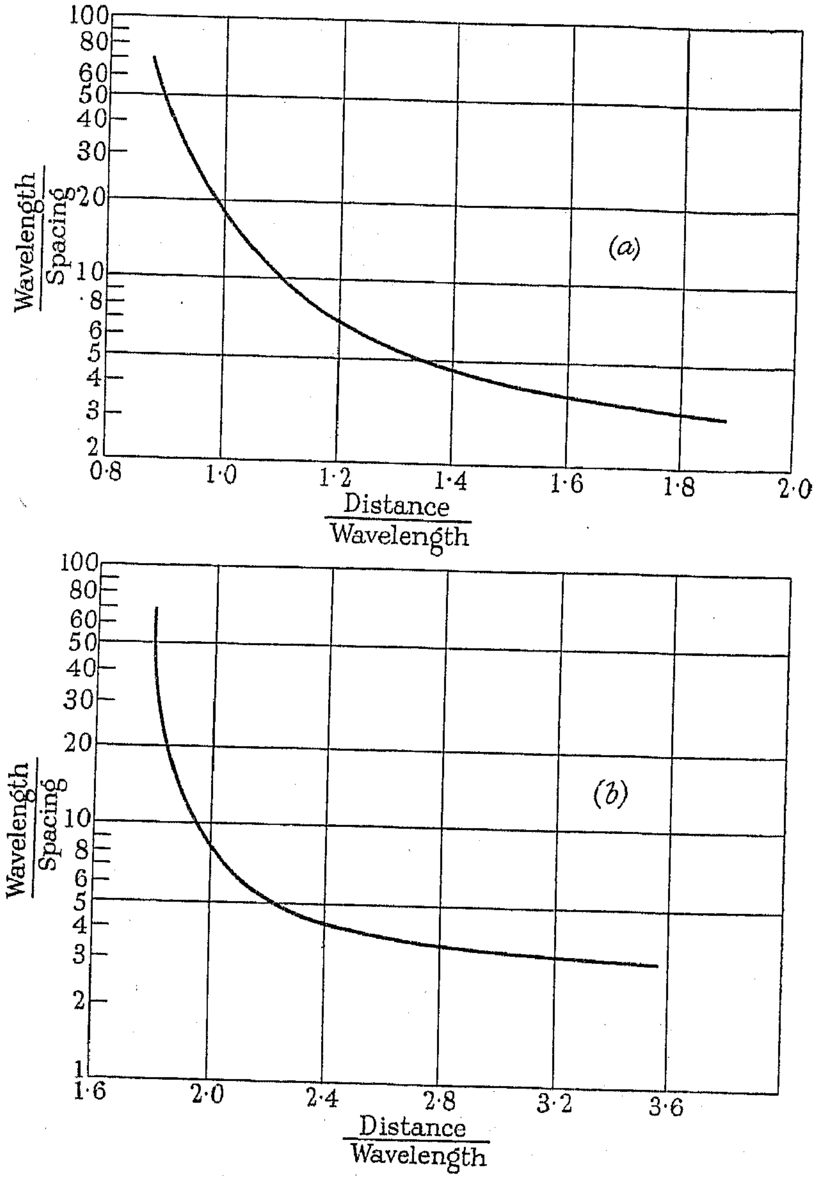

Fig. 6.—Curves showing minimum calibrating radius for an Adcock direction-finder in which ϵ_{max} is $2\cdot5^\circ$ and k_{max} is $\frac{1}{23}$.

(a) For $\frac{1}{2}^\circ$ accuracy of calibration.
(b) For $\frac{1}{4}^\circ$ accuracy.

Usually it will be found that when ϵ_{max} and k_{max} are roughly determined by the method indicated earlier in this section, one or other of these curves will be suitable. In few cases will ϵ_{max} be less than about 1°, while if ϵ_{max} is much in excess of $2\frac{1}{2}^\circ$ there is probable something badly at fault in the aerial system which should in any case be rectified before calibration.

If the value of ϵ_{max} is much less than 1° it will be permissible to choose a radius somewhere between that specified by Fig. 7 and that given in Figs. 3 and 4. In no case is it permissible to choose a radius less than that given by Figs. 3 and 4, if the accuracy of calibration is to be of the order mentioned on these curves ($\frac{1}{2}$° or $\frac{1}{4}$° as the case may be). It will be seen from the curves that the minimum radius for calibration usually lies somewhere between $0 \cdot 6\lambda$ and about $3 \cdot 5\lambda$, depending on the spacing and accuracy of aerial matching of the Adcock system.

EXPERIMENTAL WORK

A number of tests have been carried out using a four-aerial Adcock direction-finder at the Radio Research Station, Slough, to attempt to verify the conclusions arrived at theoretically in this paper. In these tests, a portable transmitter was carried along a fixed radius from the centre of the direction-finder, and the bearings obtained at different distances carefully noted. The results of two such tests are given in Fig. 8. A wavelength of 45 m. was used in these experiments, and the aerial spacing was 9 m. In Case (*a*) the direction-finder was used in its normal condition, and measurements of aerial balance made by means of a central oscillator indicated values of ϵ_{max} and k_{max} of about 1° and 1/60 respectively. The analysis given in this paper therefore predicts about 70 m. as the minimum calibrating radius for $\frac{1}{4}$° accuracy and about 50 m. for $\frac{1}{2}$° accuracy. It will be seen in Fig. 8(*a*) that, after changing rapidly at close ranges, the bearing settles down to a steady value at about 50 m. The irregularities from about 90 m. onwards are almost certainly due to irregularities of the site.

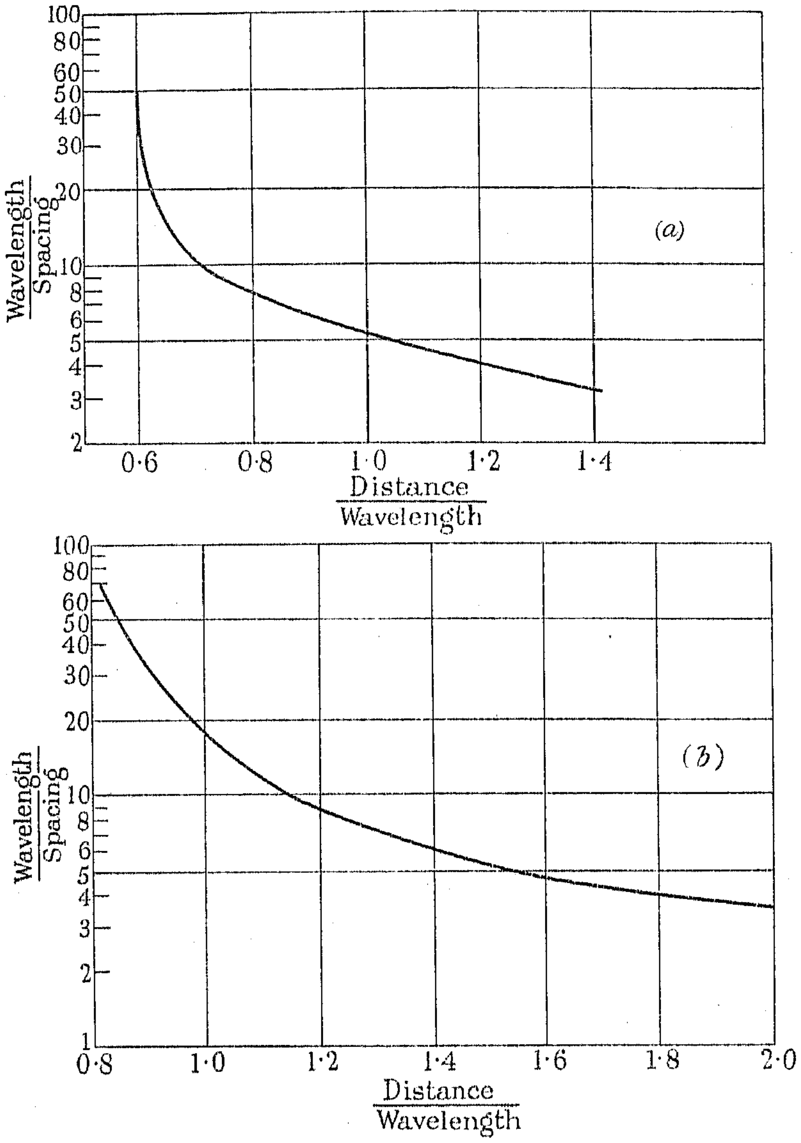

Fig. 7.—Curves showing minimum calibrating radius for an Adcock direction-finder in which $\epsilon_{max} = 1 \cdot 25°$ and $k_{max} = \frac{1}{40}$.

(*a*) For $\frac{1}{2}$° accuracy of calibration.
(*b*) For $\frac{1}{4}$° accuracy.

Theory indicates that the minimum calibrating radius is increased if the balance of the aerials of the direction-finder is disturbed. To test this, the aerial balance was deliberately upset by inserting a certain impedance in the earth lead of one aerial. The effect of this, as indicated by balance measurements made by means of the central oscillator, was to increase k_{max} to about $\frac{1}{15}$ while ϵ_{max} was of the order of 1°–2°. Theory now gives 120 m. as the minimum calibrating radius for $\frac{1}{4}$° accuracy and about 60 m. for $\frac{1}{2}$° accuracy. Fig. 8(*b*) shows that in this case the bearing had not settled down to a steady value before the irregularities of the site began to have an appreciable effect, but it is obvious that the minimum calibrating radius in Case (*b*) is greater than in Case (*a*), where a considerable portion of the curve is horizontal.

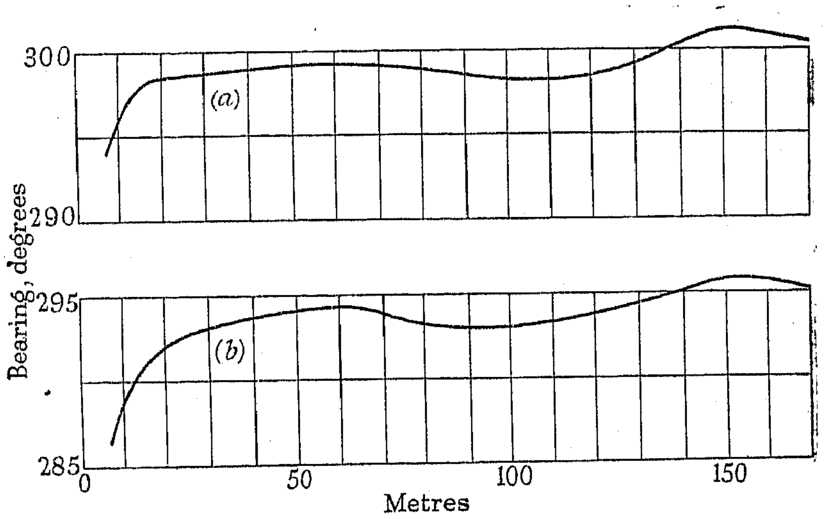

Fig. 8.—Curves showing bearing given by portable transmitter at various distances along the same radius under different conditions.

(*a*) $\lambda = 45$ m., aerial spacing = 9 m., $\epsilon_{max.} = 1°$, $k_{max.} = \frac{1}{60}$.
(*b*) As above, except that $\epsilon_{max.} = 1°$ (approx.), $k_{max.} = \frac{1}{15}$.

The curve in Fig. 8(*b*) emphasizes a point which must not be overlooked, namely that the minimum calibrating radius in any given case may well prove to be impracticable, inasmuch as it may be so great as to bring the calibrating transmitter up to or beyond the boundary of the uniform portion of the site. This will be especially likely to occur on medium and long wavelengths.

In such cases it will be best to choose a radius well within the uniform portion of the site, and from the equations given in this paper and a knowledge of ϵ_{max} and k_{max} estimate the maximum calibrating error for this distance. If ϵ_{max} and k_{max} can be measured accurately then it will be feasible to use the data here given to construct a correction curve to apply to the calibration made at close range, but in so far as the conditions which prevent the use of a sufficiently large radius will also in many cases prevent the accurate measurement of ϵ_{max} and k_{max} this will usually not be possible. In such cases all that can be done is to calculate the probable reliability of the actual calibration curve in order to estimate its usefulness.

THE EFFECTS OF GROUND ATTENUATION

As is stated earlier in the paper, the effects of ground attenuation have been neglected so far. Except on very poorly-conducting sites no appreciable error is introduced by making this assumption for distances of 1 or 2 wavelengths. On very poor sites, however, the radiation component of the electric field from a short vertical radiator will attenuate with distance more rapidly than inversely as the distance, as has been assumed throughout the paper. In the worst cases the attenuation with distance will approximate to an inverse square law. If then the ground attenuation is known to be large, it will be preferable to assume an inverse square law for the rate of decay of the electric force and to use the formulae and curves relating to the inverse square law which are given throughout the paper for the determination of the minimum radius for calibration. A slightly greater minimum radius will be obtained than for the case of the inverse distance law.

CONCLUSION

This paper shows how to determine the minimum distance from a four-aerial Adcock direction-finder at which it is possible to place a calibrating transmitter, without the proximity of the calibrating transmitter itself causing errors in calibration exceeding some specified value. Further, if the site of the direction-finder is uniform and free from obstacles for distances exceeding this minimum distance by a fair margin, a calibration made at this minimum distance will provide a curve of instrumental error to within the prescribed accuracy. It is to be noted that it is necessary for the site in the neighbourhood of the direction-finder to be uniform. Except when the soil conductivity is exceedingly low, it is not in general necessary to allow for the effects of ground attenuation.

If the site is not uniform up to distances slightly exceeding the minimum distance prescribed in this paper, as, for example, would be the case if there were buried conductors in the immediate neighbourhood of the direction-finder, then it may not be possible to perform a calibration which will determine the instrumental error of the direction-finder free from the complicated effects of site error. Even in such cases, however, calibrations made at distances less than the minimum specified in this paper will be subject to the "proximity" errors here described.

Frequently, however, as in the case of short-wave direction-finders, the necessary condition of uniformity of the site in the immediate neighbourhood of the direction-finder is satisfied. The chief object of the paper is to give guidance in these circumstances as to the choice of a suitable calibrating radius for the determination of instrumental error.

ACKNOWLEDGMENTS

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(1) R. H. Barfield and W. Ross: "A Short-wave Adcock Direction-finder," *Journal I.E.E.*, 1937, vol. 81, p. 682.

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APPENDIX I

Referring to Fig. 1, we have

$$AP^2 = \frac{s^2}{4} - rs\cos\phi + r^2$$

$$\text{whence AP} = r\left(1 - \frac{s}{2r}\cos\phi + \frac{s^2}{8r^2} - \frac{s^2}{8r^2}\cos^2\phi + \ldots\right)$$

$$= r\left(1 - \frac{s}{2r}\cos\phi + \frac{s^2}{8r^2} - \frac{s^2}{8r^2}\cos^2\phi\right)$$

up to terms of the order of $\frac{s^2}{r^2}$.

$$\text{Similarly BP} = r\left(1 + \frac{s}{2r}\cos\phi + \frac{s^2}{8r^2} - \frac{s^2}{8r^2}\cos^2\phi\right)$$

$$\text{whence} \qquad BP - AP = s\cos\phi.$$

Therefore the phase difference between the field at A and the field at B—considering one at a time, only, the three terms (inverse-distance, inverse-square, or inverse-cube terms) in the expression for the field strength due to the aerial at P—is equal to $2\pi s\cos\phi/\lambda$.

Assuming that ωt is the mean phase of the electric fields at A and B (again considering only one term at a time), the e.m.f. in pair AB is given by

$$E_1 \sin\left(\omega t + \frac{\pi s\cos\phi}{\lambda}\right) - E_2\sin\left(\omega t - \frac{\pi s\cos\phi}{\lambda}\right)$$

where E_1 and E_2 have the meaning stated on page 193. Assuming $\pi s/\lambda$ small, so that $\sin \pi s/\lambda = \pi s/\lambda$ and $\cos \pi s/\lambda = 1$, we obtain

E.M.F. in AB

$$= (E_1 + E_2)\frac{\pi s\cos\phi}{\lambda}\cos\omega t + (E_1 - E_2)\sin\omega t$$

Note that the mean phase for the fields at A and B is not quite the phase of the field at O, but differs from the latter by a term of the order of $\frac{s}{r} \times \frac{2\pi s}{\lambda}$. Similarly the mean of the phases of the fields C and D is not exactly the phase at O, nor is it exactly equal to the mean of the phases of the fields at A and B.

It is accurate enough for our purpose, however, to assume that the mean of the phases at A and B is equal to the mean of the phases at C and D, since by so doing we neglect only a small phase-difference between the resultant e.m.f.'s in AB and CD. As has been mentioned in this paper and demonstrated elsewhere,* a small phase difference between the e.m.f.'s in the two aerial pairs of a direction-finder does not, to a first approximation, produce any error in bearing. Thus the mean of the phases of the electric field at A and B may be written equal to the mean of the phases of the field at C and D, and this has been done in this paper.

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* See Reference (1).

APPENDIX II

Assuming an inverse distance law for the field strength,

$$E_1 \propto \frac{1}{\mathrm{AP}} = \frac{1}{r\left(1 - \frac{s\cos\phi}{r} + \frac{s^2}{4r^2}\right)^{\frac{1}{2}}}$$

$$= \frac{1}{r}\left[1 + \frac{s\cos\phi}{2r} - \frac{s^2}{8r^2}(1 - 3\cos^2\phi)\right]$$

Similarly $E_2 \propto \frac{1}{r}\left[1 - \frac{s\cos\phi}{2r} - \frac{s^2}{8r^2}(1 - 3\cos^2\phi)\right]$

Substitution in the expression derived in Appendix I gives equation (1).

APPENDIX III

$$\tan\phi' = \tan\phi \frac{\left\{\frac{\pi^2}{\lambda^2}\left[2 - \frac{s^2}{4r^2}(1 - 3\sin^2\phi)\right]^2 + \frac{1}{r^2}\right\}^{\frac{1}{2}}}{\left\{\frac{\pi^2}{2}\left[2 - \frac{s^2}{4r^2}(1 - 3\cos^2\phi)\right]^2 + \frac{1}{r^2}\right\}^{\frac{1}{2}}}$$

and expanding as far as terms of the order of s^2/r^2 gives

$$\tan\phi' = \tan\phi\left[1 - \frac{3s^2\cos 2\phi}{8r^2\left(1 + \frac{\lambda^2}{4\pi^2r^2}\right)}\right]$$

Now

$$\tan\phi' = \tan\left[\phi + (\phi' - \phi)\right]$$

$$= \tan\phi + (\phi' - \phi)\sec^2\phi, \text{ assuming } (\phi' - \phi) \text{ small}$$

$$= \tan\phi\left[1 + \frac{2(\phi' - \phi)}{\sin 2\phi}\right]$$

Hence $\phi' - \phi = -\frac{3}{32}\cdot\frac{s^2}{r^2}\cdot\frac{1}{1 + \frac{\lambda^2}{4\pi^2r^2}}\sin 4\phi$

APPENDIX IV

Assuming that a phase error ψ arises in the aerial C (see Fig. 1), the e.m.f. in the limb CD is

$$E_3\sin\left(\omega t + \frac{\pi s\sin\phi}{\lambda} + \psi\right) - E_4\sin\left(\omega t - \frac{\pi s\sin\phi}{\lambda}\right)$$

and, neglecting terms of the order of ψ^2, $\left(\frac{\pi s\sin\phi}{\lambda}\right)^2$, and $\frac{\psi\,.\,\pi s\sin\phi}{\lambda}$, since ψ and $\frac{\pi s\sin\phi}{\lambda}$ are both supposed to be small, this becomes

$$\left[E_3\psi + (E_3 + E_4)\frac{\pi s\sin\phi}{\lambda}\right]\cos\omega t + (E_3 - E_4)\sin\omega t$$

whence the amplitude of the e.m.f. in the pair CD is

$$Q = \left[(E_3 + E_4)^2\frac{\pi^2s^2\sin^2\phi}{\lambda^2} + (E_3 - E_4)^2\right]^{\frac{1}{2}}$$
$$\left[1 + \frac{E_3\psi(E_3 + E_4)\frac{\pi s\sin\phi}{\lambda}}{(E_3 + E_4)^2\frac{\pi^2s^2\sin^2\phi}{\lambda^2} + (E_3 - E_4)^2}\right]$$

APPENDIX V

$$\epsilon = \frac{\Delta\sin 2\phi}{2}$$

$$\epsilon' = \frac{\Delta'\sin 2\phi}{2}$$

Hence $\epsilon - \epsilon' = (\Delta - \Delta')\frac{\sin 2\phi}{2}$

$$= \frac{\Delta\sin 2\phi}{2}\left(1 - \frac{\Delta'}{\Delta}\right)$$

$$= \epsilon_{max}\cos\phi\left(1 - \frac{\Delta'}{\Delta}\right)$$

APPENDIX VI

We have the result (see page 194):—

$$\Delta' = \frac{E_3\psi(E_3 + E_4)\frac{\pi s\sin\phi}{\lambda}}{(E_3 + E_4)^2\frac{\pi^2s^2\sin^2\phi}{\lambda^2} + (E_3 - E_4)^2}$$

For the inverse distance term in the field strength,

$$E_3 \propto \frac{1}{r}\left[1 + \frac{s}{2r}\sin\phi - \frac{s^2}{8r^2}(1 - 3\sin^2\phi)\right]$$

$$E_3 + E_4 \propto \frac{1}{r}\left[2 - \frac{s^2}{4r^2}(1 - 3\sin^2\phi)\right.$$

$$E_3 - E_4 \propto \frac{1}{r}\left[\frac{s}{r}\sin\phi\right]$$

Substitution in the equation for Δ', and writing

$$\Delta = \frac{\psi}{(2\pi s\sin\phi)/\lambda}$$

gives the result

$$\frac{\Delta'}{\Delta} = \left(1 + \frac{s}{2r}\sin\phi - \frac{\lambda^2}{4\pi^2r^2}\right)$$

up to terms of the first order in s/r and including the term $\lambda^2/(4\pi^2r^2)$.

APPENDIX VII

The quantity $(\epsilon - \epsilon')$ is of the form

$$p\cos\phi - \frac{q\sin 2\phi}{2}$$

Differentiating with respect to ϕ, we find that this expression has turning points at ϕ given by

$$\sin\phi = \frac{p \pm \sqrt{(p^2 + 8q^2)}}{4q}$$

Now p and q are positive, and by further differentiation it is easily seen that the maximum occurs where

$$\sin\phi = \frac{p - \sqrt{(p^2 + 8q^2)}}{4q}$$

APPENDIX VIII

We have (inverse distance law)

$$E_3 \propto \frac{1}{r}\left[1 + \frac{s}{2r}\sin\phi - \frac{s^2}{8r^2}(1 - 3\sin^2\phi)\right]$$

$$E_4 \propto \frac{1}{r}\left[1 - \frac{s}{2r}\sin\phi - \frac{s^2}{8r^2}(1 - 3\sin^2\phi)\right]$$

up to terms of the order of s^2/r^2.

Hence

$$E_3(1 + \delta) + E_4 \propto \frac{1}{r}\left[2 - \frac{s^2}{4r^2}(1 - 3\sin^2\phi) + \delta + \frac{\delta s\sin\phi}{2r}\right]$$

neglecting terms of the order of $\delta s^2/r^2$.

Also $E_3(1 + \delta) - E_4 \propto \frac{1}{r}\left(\frac{s\sin\phi}{r} + \delta + \frac{\delta s\sin\phi}{2r}\right)$

Whence the result given in the text follows.

APPENDIX IX

$$r^2Q^2 = \frac{4\pi^2 s^2\sin^2\phi}{\lambda^2}\left[1 - \frac{s^2}{4r^2}(1 - 3\sin^2\phi) + \delta\right] + \left[\frac{s^2\sin^2\phi}{r^2} + \frac{2\delta s\sin\phi}{r} + \delta^2\right]$$

Write $\frac{4\pi^2 s^2\sin^2\phi}{\lambda^2} = U^2$

$$r^2Q^2 = U^2\left[1 - \frac{s^2}{4r^2}(1 - 3\sin^2\phi) + \frac{\lambda^2}{4\pi^2r^2}\right] + \delta\left(U^2 + \frac{2s\sin\phi}{r}\right) + \delta^2$$

$$r^2Q^2 = U^2\left[1 - \frac{s^2}{4r^2}(1 - 3\sin^2\phi) + \frac{\lambda^2}{4\pi^2r^2}\right]\left\{1 + \frac{\delta\left[U^2 + \frac{2s\sin\phi}{r}\right] + \delta^2}{U^2\left[1 - \frac{s^2}{4r^2}(1 - 3\sin^2\phi) + \frac{\lambda^2}{4\pi^2r^2}\right]}\right\}$$

$$= U^2\left\{1 - \frac{s^2}{4r^2}(1 - 3\sin^2\phi) + \frac{\lambda^2}{4\pi^2r^2}\right\}\left\{1 + 2\Delta'\right\}$$

Hence the expression for Δ' given on page 196.

APPENDIX X

This follows from the results given in the paper quoted in Reference (1), because if Δ' is the amplitude error of the e.m.f. in CD relative to the e.m.f. in AB, and η' is the error produced thereby,

$$\eta' = \frac{\Delta'\sin 2\phi}{2}$$

If Δ = value of Δ' when $r \to \infty$, and η is the corresponding error,

$$\eta = \frac{\Delta\sin 2\phi}{2}$$

Hence the result quoted on page 196.

[The discussion on this paper will be found on page 207.]

SYMPOSIUM ON RADIO DIRECTION-FINDING

INTRODUCTORY REMARKS OF DR. R. L. SMITH-ROSE, Member.

(The papers comprising the Symposium were read before the WIRELESS SECTION *on the 1st March,* 1939.)

GENERAL

The six papers which I have to present to you describe the results of investigations in radio direction-finding carried out by the Radio Department of the National Physical Laboratory during the past few years. The references to the papers, arranged in order of publication, are as follows:—

(1) R. H. BARFIELD and R. A. FEREDAY: " An Improved Medium-Wave Adcock Direction-Finder," *Journal I.E.E.*, 1937, vol. 81, p. 676.
(2) R. H. BARFIELD and W. ROSS: " A Short-Wave Adcock Direction-Finder," *ibid.*, 1937, vol. 81, p. 682.
(3) R. L. SMITH-ROSE and H. G. HOPKINS: " Radio Direction-Finding on Wavelengths between 6 and 10 Metres (Frequencies 50 to 30 Mc./sec.)," *ibid.*, 1938, vol. 83, p. 87.
(4) R. H. BARFIELD and W. ROSS: " The Measurement of the Lateral Deviation of Radio Waves by Means of a Spaced-Loop Direction-Finder," *ibid.*, 1938, vol. 83, p. 98.
(5) R. A. FEREDAY: " A Sense-Finding Device for use with Spaced-Aerial Direction-Finders," *ibid.*, 1939, vol. 84, p. 96.
(6) W. ROSS: " The Calibration of Four-Aerial Adcock Direction-Finders," *ibid.*, 1939, vol. 85, p. 192.

I propose not to deal with the papers strictly in the above order, but to rearrange them in a manner more convenient for this discussion. Before surveying the actual subject-matter of the papers, however, I should like to make a very brief reference to the history of modern direction-finding with the view of forming a background which I think is appropriate to the present discussion.

The closed-loop direction-finder was devised as a practical instrument before the War and used chiefly as an aid to marine navigation. During the period 1914–18 development was rapid and the application of the art became widespread. During this period it was discovered that the instrument was subject to certain limitations, in so far as the observed bearings of fixed transmitting stations were found to vary considerably during the night and the transition periods of sunrise and sunset. Similar effects were noticed in taking bearings on the transmissions from aircraft at appreciable angles of elevation, and it was this phenomenon that inspired F. Adcock to devise his now well-known system of direction-finding, the fundamental principles of which were disclosed in British Patent No. 130490, for which he applied in August, 1918. Adcock's conception of the cause of the phenomenon was so complete that even after 20 years it is quite true to state that all direction-finders of this type differ only in details of design from the various forms described in his original patent.

At about the same time that Adcock was studying means for eliminating the so-called " aeroplane effect " in direction-finding, T. L. Eckersley was studying the corresponding night effects; and with characteristic foresight he devised an alternative means of avoiding or reducing the errors resulting from these effects. In a paper[*] published in 1921, Eckersley described experiments made with a pair of vertical loops, spaced a short distance apart and connected together in opposition. Thus was born the spaced-loop direction-finder which has recently become so useful as a research tool in studying wave propagation phenomena and their effect on direction-finding.

In a paper[†] on the elimination of wave polarization errors in direction-finding published in 1926, R. H. Barfield and I described experiments carried out with both Adcock's and Eckersley's arrangements referred to above. On account of its greater sensitivity the Adcock instrument became more immediately of practical use, but Eckersley's spaced-loop instrument has now recovered from this disadvantage. The papers which we are here to discuss to-night deal with some of the most recent developments of these instruments, as well as with the general extension of the radio direction-finder to shorter and shorter wavelengths.

" AN IMPROVED MEDIUM-WAVE ADCOCK DIRECTION-FINDER " (Paper No. 1)

This paper describes a practical form of Adcock spaced-aerial direction-finder covering a wavelength range of 750 to 2 000 m. (150 to 400 kc./sec.). The design of the system is based upon the principles worked out and described in a previous publication. From the circuit diagram of one half of the aerial system shown in Fig. 1[‡] it will be seen that the balanced-coupled arrangement has been employed, since earlier investigations had shown that this was less subject to polarization error than any alternative practical arrangement. Screened transformers are used to couple the aerials to the transmission lines, and additional balancing condensers of small capacitance are connected across the primaries of these transformers. Three means have been adopted to make as large as possible the pick-up factor of the system, i.e. the quotient of the voltage V (Fig. 1) by the field strength ϵ acting on the aerials. In the first place, the aerials are of unusually high capacitance, obtained by making each of them in the form of a cage of octagonal section of 4 ft. side; secondly, the aerial circuit has been arranged to resonate at a frequency of about 120 kc./sec.; and thirdly, the resonant frequency of the secondary circuit is just above the highest frequency of operation. By effecting a compromise in the two latter adjustments, a reasonably constant pick-up factor can be obtained, in spite of the inevitable tendency for this quantity to fall off as the frequency is decreased over the operating band, due to the diminishing ratio of aerial spacing to wavelength.

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[*] T. L. ECKERSLEY: " The Effect of the Heaviside Layer on the Apparent Direction of Electromagnetic Waves," *Radio Review*, 1921, vol. 2, p. 231.

[†] R. L. SMITH-ROSE and R. H. BARFIELD: " The Cause and Elimination of Night Errors in Radio Direction-Finding," *Journal I.E.E.*, 1926, vol. 64, p. 831.

[‡] These numbers throughout refer to the figure numbers of the published paper.

The system to which the paper refers was constructed with four aerials some 25 m. high, spaced at the corners of a square of 100 m. diagonal. The pick-up factor of the operating band is shown by the solid line in Fig. 3. By restricting the working range and permitting a correspondingly closer approach of aerial and line resonances, the pick-up factor may be increased up to a value of 15 m., which is the order of the value obtained with a highly efficient multi-turn tuned loop 1 m^2 in area. The broken curve in Fig. 3 indicates the extent to which the factor may be improved at the higher frequencies by partially tuning the transmission lines. In order to obtain high instrumental accuracy with any Adcock direction-finder, it is necessary to ensure exact equivalence of the four individual aerials. The principle of one of the methods used to attain this end in the present system is indicated in Fig. 4, injection from a centrally-located oscillator being used to obtain an accurate balance between the opposite aerials of each pair. Fig. 5 indicates the degree of balance which has been attained in the system described, and it also indicates the degree of balance necessary to ensure instrumental errors of less than 0·5 deg., 1 deg., and 2 deg. respectively, when waves are arriving at the aerial system at angles of incidence not less than 45°. It will be seen that an instrumental accuracy of less than 1 deg. has been realized over practically the whole frequency range. The standard wave polarization error of the installation has been found to be less than 1 deg., and accurate bearings can be observed under favourable conditions on field strengths down to 1 μV/m. The instrument thus appears to be capable of fulfilling most practical requirements as an accurate direction-finder in the medium-wave band.

"A SHORT-WAVE ADCOCK DIRECTION-FINDER" (Paper No. 2)

The second paper in the series describes a somewhat similar Adcock direction-finder for practical operation over the wavelength range of 35 to 70 m. (frequency 4·3 to 8·6 Mc./sec.). Various modifications had to be made to the general principle of the medium-wave instrument in order to overcome the technical difficulties which are encountered in extending the operation to shorter wavelengths. The schematic circuit diagram of one half of the aerial system is shown in Fig. 1,* from which it will be seen that it differs in several details from the arrangement used on medium wavelengths. The aerial circuit is still adjusted to resonate at a frequency just below the lower end of the band employed, but no attempt at balancing is made, since in the present case a complex impedance would be necessary in place of the simple capacitance introduced in the earth lead in the medium-wave case. In this matter some accuracy in respect of polarization error has had to be sacrificed in order to secure simplicity of construction and operation. Reverting to Fig. 1, it will be seen that the aerial coupling transformers have been set a short distance in towards the centre of the system. By this arrangement the length of the secondary circuit is reduced, and also the screen surrounding the transmission lines is made shorter, thus increasing its impedance viewed as a horizontal aerial, and also reducing the coupling between the screen and the vertical aerials. All these factors tend to reduce the liability of the system to receive horizontally polarized radiation. It is further to be noted that the whole of the receiver at the centre of the system is placed inside a wire-netting screen of sufficient dimensions to contain the operator. Tests have shown that the presence of this screen has a negligible effect on the performance of the system.

The aerials, which are about 10 m. high and spaced 10 m. apart, are of metal tubing supported only from the wooden hut containing the receiving gear. The method by which each aerial and its associated earth is connected to the transmission line, and this in turn is led into the receiving hut, is shown in Fig. 4. It will be noted that a small oscillator with a short vertical aerial is mounted outside the receiving screen in a position exactly symmetrical with respect to all four aerials. This provides a suitable means of balancing up the aerial system, which has advantages of simplicity and improved accuracy over the direct injection method described in the previous paper. A special type of goniometer, indicated diagrammatically in Fig. 5, was designed and constructed for use in this short-wave installation. Two field coils, each with an associated search coil, are mounted one above the other on the same spindle but in separate screened compartments. There is a screening cage between each field coil and its search coil; the two search coils are connected in parallel and leads are brought out to terminals through suitable slip-rings.

A detailed investigation of the instrumental error of this direction-finding system has been carried out, and the results of the analytical and experimental work are described in the paper. It is shown that the actual instrumental error varies with the direction of arrival of the waves relative to the aerial system, but the maximum value of the error realized is about 2·5 deg. The standard-wave error due to polarization effects varies between 1 deg. and 4 deg., being greatest at the longer wavelengths. The pick-up factor of the aerial and associated system is about 4 m. at the longer wavelengths, rising to 10 m. at the lower end of the wavelength band. This compares favourably with the value of 3 to 5 m. obtained with the medium-wave system. The resulting sensitivity of this short-wave installation is such that in the presence of an incoming field strength of 1 μV/m., bearings may be observed with a swing at the signal minimum of ± 5 deg.; and the optimum accuracy of the instrument may be utilized with field strengths of 10 μV/m. or more.

In concluding this section, it may be remarked that the above direction-finding system has now been supplemented with a separate double receiver and cathode-ray tube visual indicator, a description of which has been given elsewhere.* By means of this apparatus, visually-indicated bearings may be observed to an accuracy of about 2 deg., with an incoming field intensity of 10 μV/m.; but bearings to a somewhat lower accuracy may be estimated with a field intensity of 1 μV/m.

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* These numbers throughout refer to the figure numbers of the published paper.

"A SENSE-FINDING DEVICE FOR USE WITH SPACED-AERIAL DIRECTION-FINDERS" (Paper No. 5)

It is well known that there are certain limitations in the use of the ordinary sense-finding arrangements at short wavelengths, owing to difficulties in maintaining the correct phase relationships between the currents in the spaced and auxiliary aerials necessary to give the familiar cardioid-diagram conditions. Hence, in connection with the short-wave direction-finder just described, it was found desirable to develop a means for determining the sense of the observed bearings, which should if possible be free from the above limitations. The application of the new method to the aural direction-finder consists in replacing one of the pairs of spaced vertical aerials by a single central vertical aerial and connecting this to earth through the goniometer field coils rendered vacant by the change of connections. The search coil of the goniometer is then rotated to a signal minimum position, which when compared with the original minimum position used for the bearing observation gives the sense of the latter directly. In the case of the short-wave Adcock direction-finder it has been found convenient to use the released pair of spaced aerials, with their connection reversed so as to be additive instead of in opposition as the equivalent central vertical aerial indicated in Fig. 6. Suitable resistances are connected at the base of each aerial in order to ensure the correct phase relationship for obtaining a signal minimum on the goniometer. In practice, these resistances, of about 5 000 ohms in value, are permanently introduced in each of the four aerials (see Fig. 6), and centrally-controlled relays are arranged to short-circuit these when the aerials are used in the usual direction-finding arrangements.

The operation of the above method is indicated by the diagrams in Fig. 1, (*a*) indicating the true direction of arrival of the signal, and (*b*) and (*c*) the direction of the "sense" minimum position for the alternative modes of combining one pair of spaced aerials with the central omni-directional aerial. The shading of the diagrams indicates the quadrants of the sense indication which applies to the bearing. In the actual set-up of the device the switching of the aerials is carried out from the goniometer position, and simultaneously, small dials are illuminated to indicate the appropriate positions shown in Figs. 1(*a*) and 1(*b*). Either pair of spaced aerials can be switched to the sense position, and this is sometimes very helpful in determining the sense of a bearing which nearly coincides with either the N.-S. or E.-W. direction.

Experimental tests made on signals from various short-wave transmitting stations have shown that this arrangement works very well over the whole range of wavelengths of the direction-finder. The sense-finding device is equally applicable to the visual indicating instrument, and it has been operating satisfactorily for the past year or more on both the aural and the visual systems.

"THE CALIBRATION OF FOUR-AERIAL ADCOCK DIRECTION-FINDERS" (Paper No. 6)

In order that bearings may be observed on a radio direction-finder to the highest accuracy possible, it is necessary that the whole installation shall be calibrated in a satisfactory manner. Such a calibration will, in general, cover two classes of error; one, termed the instrumental error, is associated with the whole installation as such; and the second is any error arising from irregularities or non-uniformities in the site of the direction-finder, such site being arbitrarily taken to cover the locality within a radius of about $\frac{1}{4}$ mile. Experience in direction-finding extending over many years has shown that the question of site error is beset with many difficulties which arise essentially from the serious departure of our world from an ideal, perfectly smooth, uniformly conducting sphere. The subject is under intensive investigation at the present time by our own and other research organizations, and I propose, therefore, not to deal with site errors and calibrations in the present discussion.

It must be realized, however, that in order to study the inherent instrumental error of a direction-finder it is essential to have a clear, uniform, and level site so that a calibrating transmitter may be taken to various positions around the installation. In order that the radiation received at the direction-finder from this transmitter may not be influenced to any appreciable extent by undesirable obstacles or irregularities in the proximity of the boundary of uniform site, it is clearly desirable that the distance of the calibrating transmitter should be as short as possible. If the range is made too short, however, spurious errors may arise owing to the fact that the field from the calibrating transmitter has not then the same value at all four aerials of the Adcock direction-finder. The present paper describes an analytical investigation of this problem, with a view to determining the minimum distance which may safely be used in such calibration. The limitation does not, of course, arise in the case of the rotating "H" type of direction-finder.

The effect of the proximity of the calibrating oscillator is of two kinds; it may introduce an additional error in the readings on the direction-finder or it may modify certain existing instrumental errors, e.g. that due to mismatch between the two members of one pair of aerials. These two effects are examined separately in the paper, and the results are presented in the form of the graphs shown in Figs. 2–5. These curves show the relation between the minimum distance of the calibrating transmitter and the spacing of the direction-finding aerial system, in order to ensure that the addition to or modification of the instrumental error shall not exceed certain specified values. In the practical application of the results of this analysis, the errors determined in the above manner must be added together in order to show the total error which arises from the proximity of the calibrating transmitter. The minimum distance at which this transmitter may be placed during calibration will obviously depend upon the maximum permissible value of this error, which in turn depends upon the inherent instrumental accuracy of the direction-finding system. Curves calculated for two typical cases and for two calibration accuracies are shown in Figs. 6 and 7. It will be seen from these curves that the minimum radius for calibration lies somewhere between 0·6 and 3·5 times the wavelength on which the direction-finding is carried out. Experimental tests on a wavelength of 45 m. (6·7 Mc./sec.) have shown such general agreement with this result as to justify its adoption in practice. It is evident, however, that limitations of site conditions already referred to may preclude the fulfilment of these conditions on medium and long wavelengths. In such cases the data given in the paper are useful in calculating the probable reliability of a calibration carried out at less than the specified radius for the appropriate conditions.

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* "A Short-Wave Cathode-Ray Direction-Finding Receiver," *Wireless Engineer*, 1938, vol. 15, p. 432.

"RADIO DIRECTION-FINDING ON WAVELENGTHS BETWEEN 6 AND 10 METRES"

(Paper No. 3)

With the introduction of wavelengths below 10 m. into the sphere of practical radio-communication, it has seemed useful to explore the possibilities of ultra-short-wave direction-finding. To this end, instruments have been developed for the wavelength range 6 to 10 m. (50 to 30 Mc./sec.), and used in a preliminary survey of the subject. The two instruments described in the paper now under discussion are of a transportable type using a rotating aerial system, comprising a closed loop and an "H" type of spaced aerial, respectively. While care is needed in the design and construction of the instruments to secure electrical symmetry and stability of operation, no difficulties are encountered other than those normally associated with ultra-short-wave technique. The arrangement of the direction-finders is shown in Figs. 2 and 3 of the paper. The aerial system is mounted rigidly to the frequency-changer stage, the whole rotating on a suitable turn-table mounted on a tripod. A flexible transmission line carries the output from this to a combined intermediate- and audio-frequency unit fixed on the ground.

The majority of the experimental work described in the paper was carried out with the loop set, which has a pick-up factor of 6 to 10 m. and an overall sensitivity such that bearings with a swing of ± 10 deg. can be taken with a field strength of 1 μV/m. With a stronger field of 10 μV/m. the corresponding swing is reduced to ± 2·5 deg. The inherent instrumental accuracy of the set is between 1 deg. and 2 deg., but some difficulty is usually experienced in finding a suitable site on the ground at which such an accuracy can be utilized. For short-distance working it is important also that the site of the transmitter should be reasonably free from disturbing obstacles or irregularities. With the loop direction-finder set up at various ground sites, the bearings have been observed of some ground transmitting stations using vertical aerial systems. At distances up to 35 km. the errors were found to range up to 8 deg., although in the majority of cases the errors were less than 2 deg. The variations in bearings from day to day did not exceed about 2 deg. Under certain conditions, bearings have also been observed on commercial transmitting stations some 5 000 km. away, and in these cases much larger errors and variations were observed.

When a horizontal aerial has been used at the transmitting station serious errors ranging up to nearly 80 deg. have been observed with the loop direction-finder. These errors are attributable to the reception of horizontally polarized waves, and they may be avoided by using a spaced-aerial or Adcock direction-finder of the type described in the paper. This latter instrument has recently been developed in an improved and more sensitive form, and a further study has been made of the effects on direction-finders of horizontally polarized ultra-short waves. An improved form of the rotating-loop instrument developed for a particular application of fixed ground-station working has been described elsewhere.* The instrument has a somewhat greater sensitivity than the transportable model, and an instrumental accuracy of a fraction of 1 deg. has been attained by careful design and rigid mounting of the various portions of the installation.

"THE MEASUREMENT OF THE LATERAL DEVIATION OF RADIO WAVES BY MEANS OF A SPACED-LOOP DIRECTION-FINDER" (Paper No. 4)

The general objective in the work on the development of the Adcock direction-finder has been to produce an instrument of the highest attainable accuracy. It must be realized, however, that the limit of application of such an instrument may be set by phenomena accompanying the propagation of waves. It is evidently of little use to attempt to improve the accuracy of determination of the vertical plane containing the direction of arrival of the waves if the direction of the transmitting station does not also lie in this plane. Previous workers had shown that, under certain conditions, radio waves are subject to a certain amount of lateral deviation from the great-circle plane between transmitter and receiver, and the present investigation was conducted with a view to examining this deviation in more detail. For this purpose it was necessary to have available direction-finding apparatus of the highest instrumental accuracy, particularly as regards polarization and other variable errors. An improved model of the spaced-loop direction-finder of the type first employed by T. L. Eckersley appeared to be suitable for this purpose, since the loops could be arranged to have greater symmetry than vertical aerials, and also to have a much smaller coupling.

The experimental equipment developed and set up at the Radio Research Station, Slough, is shown diagrammatically in Fig. 2. It comprises four screened loops, each 1 m. square, arranged at the corners of a square of 12 m. diagonal. The loops are tuned by remote control and are coupled by screened transmission lines to the receiver, which is of the cathode-ray visual indicating type already mentioned. The four loops are aligned in parallel vertical planes, and a central oscillator is mounted over the screened receiver, for accurately matching the loops and balancing the whole system. The wavelength band covered by the installation is from 30 to 100 m. (3 to 10 Mc./sec.) and the pick-up factor varies from about 1 m. at the long-wave to 6 m. at the short-wave end of the band. A detailed examination of the apparatus has shown that the variations in apparent bearings which can arise from instrumental causes have a maximum of about

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* H. G. Hopkins: "A Loop Direction-Finder for Ultra-Short Waves," *Wireless Engineer*, 1938, vol. 15, p. 651.

2 deg., and they are usually not in excess of 1 deg. It may be remarked that, in dealing with radiation received from the ionosphere, this system operates equally well with either vertically or horizontally polarized waves.

Numerous observations have been made with this apparatus on signals received from various transmitting stations at distances of 160 to 5 000 km., and the results show that deviations much in excess of the possible instrumental error have been experienced. These deviations were on occasions as much as 10–20 deg. in the case of the distant stations, and up to 50 deg. in the case of one station at the shortest range. They are apparently due to the reception of waves reflected or scattered from the ionosphere at points to one side or the other of the great-circle path. The most serious deviations of the waves from the true bearing occur when the receiver is within the skip distance from the transmitter. The type of trace which is obtained on the cathode-ray tube during the observations is illustrated in Plates 1 and 2 accompanying the paper. It will be seen from these photographs that sometimes two distinct signals are received, giving different apparent bearings. These signals are evidently the result of first- and second-order reflections from the ionosphere, the point of reflection or scattering not necessarily being the same for the two sets of waves. Except when the receiver is within the skip distance from the transmitter, the largest errors are usually accompanied by appreciable fading of the resulting signal, and it is found that by rejecting those observations for which the amplitude is less than 0·7 times the maximum, fairly good general accuracy of bearing determination is obtained. For example, in the case of signals from two German transmitting stations, some 70–85 % of the observed bearings differed by less than 2 deg. from the mean bearing. In the case of reception from American stations, some 40 % of the observed bearings were within 2 deg., and about 75 % within 5 deg., of the mean bearing. When observations were taken on signals from Dorchester at a distance of 160 km., the apparent bearing was frequently subject to a steady drift from one side to the other of the true bearing over an arc of 50–60 deg.

The pulse signals emitted by this station made it possible to study more easily the various echo signals received, and it was found that when more than one ray was being received the bearings observed on the two rays were frequently different—sometimes by as much as 10–20 deg.

It should be pointed out that the effects illustrated by the results described in the paper are possibly exaggerated by the fact that many of the transmitting stations on which observations were made, emit concentrated beams of radiation which will, so to speak, illuminate brightly certain portions of the ionosphere, from which greatly increased scattering might be expected. But the results of such an investigation are very useful in assisting our study of the nature of the propagation of radio waves, in addition to illustrating the type of effects to be expected in the use of radio direction-finding under the conditions specified. It is with this dual object in view that the investigations are being continued with improved apparatus and over a much wider wavelength-band than that so far studied.

DISCUSSION BEFORE THE WIRELESS SECTION, 1ST MARCH, 1939

Mr. T. L. Eckersley: The first paper gives the practical outcome, in the form of a long-wave direction-finder, of the tests—with elevated aerial—for the polarization errors and their consequent reduction. This test is an original and systematic method of dealing with these errors, and can be used for estimating the success of various devices for eliminating them. Without such a test apparatus the improvements are mainly guesswork. The accuracy and freedom from polarization error of the aerial produced testify to the efficiency and success of the test method used. This method constitutes a very considerable advance in the technique of dealing with and eliminating the polarization errors of Adcock direction-finders.

The fact that a systematic comparison between an aerial corrected by this method and one of greater intrinsic polarization error on long-distance night signals does not show up the expected improvement is, perhaps, the first indication that true lateral deviations do occur which are not eliminated by mere attention to polarization error.

The same methods when applied to the short-wave Adcock system have again produced a direction-finder of good performance.

The attack on ultra-short-wave direction-finding indicates results of great interest and shows that the instrumental accuracy of the frame and elevated "H" type of aerial can approach that of the longer-wave direction-finders, but that the "path errors" are of increasing seriousness in ultra-short-wave transmission.

It may be of interest to compare these results with those given by W. Beuerman ("Gesammelte Vorträge der Hauptversammlung der Lilienthal Geselschaft," p. 346, published in Berlin). Without making an accurate comparison, it would appear that Beuerman's results are of the same order of accuracy as those of Smith-Rose. These results were obtained with a balanced "H" type of aerial similar to the one described by Smith-Rose, on an aeroplane flying at distances up to 200 km.

The final paper, by Mr. Ross, shows a true appreciation of the instrumental errors to be expected in a "four poster" installation, although perhaps the treatment is unduly simplified.

The aim of direction-finding research has always been towards finding out the cause of errors and, if possible, how they may be eliminated. In the past all the errors were mixed up together, and it was therefore difficult to know how to attack them. I consider that the great advance has been in the use of spaced frames, whereby the polarization error is eliminated. The spaced-frame direction-finder gives the true direction of propagation of energy at any moment, which is also the direction perpendicular to the phase surfaces.

The application of the spaced-frame method to direction-finding which is discussed in the fourth paper seems to me to perpetuate the faults of Adcock aerials (with their inherent inaccuracy on high-angle signals) without gaining the accuracy and simplicity of the true spaced-frame system. The differences between the two systems may be expressed in the statement that the true spaced-frame system uses the phase balance between two aerials (and really does measure the difference in phase), while the " four poster " system of the Radio Research Board depends on the amplitude balance of two pairs of spaced frames.

Like ordinary Adcock aerials, this system fails on high-angle transmissions in virtue of the fact that if the angles are high enough (or the incidence small enough) there is nothing in the way of amplitudes left to compare. The spurious effects, e.g. residual polarization error and inequalities in the pick-up of the individual aerials or residual pick-up by the amplifier, remain and do not fall to zero as the angle of elevation increases to 90°. The system must fail when the angles of incidence are small enough. There always must be an angle at which the wanted pick-up becomes comparable or small compared with the spurious one, since the wanted signal varies as $\sin^2 \theta$ (for the ordinary Adcock), and as $\sin \theta$ for the spaced-frame system, and the unwanted signal only varies slightly with θ.

The greater errors on Dorchester recorded by the Radio Research Board are, I think, mainly caused by these effects. Nevertheless, the Board's results and our own (to be described later) prove that waves passing through the ionosphere suffer lateral deviation.

The other factor in regard to which the four-poster method fails is that it is almost impossible to make four individual elements exactly equal electrically. In the spaced-frame method (phase comparison), although it is desirable to have the two sides equal, the method of lining up makes this unnecessary. That the lining-up or " handling " error of the rotating spaced-frame system (e.g. at Beddels End, near Chelmsford) is very small has been shown by J. W. Cox, who in a number of observations on Ongar GOQ obtained an average lining-up error of 0·16°. The mean error of 14 widely spaced observations (over a period of 6 months) is 0·044° (or about 2·7′ of arc).

I consider that in the spaced-frame system, properly used, we have an apparatus capable of determining within about 0·2° the true direction of energy flow, i.e. capable of giving the irreducible errors in transmission (" irreducible " because no improvement of the instrumental performance will eliminate them). For rays passing over the surface of the ground these errors may be of the order of 1° to 4°, on wavelengths of 20 to 100 m.

The direction of free rays, i.e. rays of such a high angle that they only come into contact with the ground at the receiver (e.g. rays from aeroplanes), can be accurately determined within a fraction of a degree. The condition that a ray is essentially free can be fixed when the wavelength, the distance it passes from obstacles, and the size of these, are known. This statement is based partly on the evidence of directional measurements made on high-angle rays from Dorchester and partly on theoretical knowledge of diffraction and the effect of obstacles in transmission. This evidence should be checked by aeroplane transmissions.

There is a point I wish to make with regard to the photographic technique of " snapshot bearings " adopted by the Radio Research Board. I doubt whether all such bearings on the direction of waves reflected from the ionosphere are related to the true direction. The mean of a large number of such snapshots is required. The process used by the Board of rejecting weak signals eliminates the worst deviations from the mean, but it is rather arbitrary. Because any ray reflected from the ionosphere is composite and spread over a cone, the relative phases and amplitudes are not definitely correlated at any two neighbouring points. Momentarily the phases may bear any relations, but on the average, they are related within a certain degree of accuracy with the mean ray direction. Averaging will tend to eliminate the irregularities which snapshots show. Perhaps some of the variations on Dorchester which are larger than ours may be caused by the snapshot method of recording employed by the Board.

Mr. J. W. Cox: In using the rotating spaced-frame system, we came across the same sort of problem of calibrating on a local transmitter as is dealt with in the paper by Mr. Ross, and it was possible to make a numerical check on the accuracy with which the field in the neighbourhood of a transmitter can be represented by the ordinary Hertz formula. The paper deals with the three terms in that formula separately, and so does not actually calculate the field acting on the Adcock aerials that are being considered. It is important to note that near to the transmitter the phase does not vary in a linear manner on the ground as it does in the case of an ordinary plane wave. It was by measuring this non-linearity of the phase that we were able to obtain a check upon the accuracy.

This was done in the following way: When the frames have been set so that there is no phase difference between them (we can find the position by lining up beforehand), they must be perpendicular to the direction from which the wave is coming, i.e. they must be lying along the constant-phase surface. If the frames are rotated about the central axis through a small angle, a phase-change is produced in them which can be measured. In the same way, if we put a small transmitting aerial at no great distance from the system but at equal distances from the frames, we expect to get again the same phase on the two aerials; but if we rotate through the same angle as before, the phase-change produced will not be the same as it is on waves from a distant transmitter. I have made such an experiment, and have expressed the results in the form of the ratio of the value obtained on a nearby transmitter at several different distances to the value recorded on a distant transmitter. The agreement between the calculated and observed results was very close, and showed that the calculation is accurate up to a distance of $\frac{1}{3}$ wavelength.

It is pointed out in the paper by Mr. Ross that it may on many occasions be difficult or even impossible to get far enough away from the system to be beyond his minimum radius. As this experiment shows that the theory can be used to calculate the field phase it should also give the field intensity, and it might be worth while to do it completely and use the results for calibrating an Adcock aerial by a transmitter which is quite close to the site.

We have been making experiments to determine the effect which local irregularities of the ground exert on the spaced-frame system. In some measurements on a local transmitter installed on a good site about 200 yd. from the system, at various azimuths, with wavelengths from 20 m. to 70 m., we found that in no case was the error more than 1°, and in most instances it was considerably less. We also took a series of bearings (similar to that shown in Fig. 8 of Mr. Ross's paper) along one direction with a wavelength of 60 m., and up to about 500 yd. away on one side and 700 yd. away on the other. Again the errors were irregular and of about the same size, i.e. in no case more than 1°, and in most cases considerably less.

Mr. F. S. Barton: I think that we must all appreciate that the Radio Research Board have not been trying to design practical direction-finders; their object has been to make tools for the purposes of investigation. I should like here to make a plea for pure research. Mr. Crompton, the President of the Massachusetts Institute of Technology, remarked recently that nothing worth while ever came out of research directed towards an object. As an illustration, he said that if 50 years ago the lighting trade had carried out research with a view to improving lighting, it would have dealt with oil, wicks, glass chimneys, and so on, and the last thing which would have been considered would have been electrons and discharges through gases. That remark supports my plea for a pure and disinterested outlook on this problem.

Mr. F. T. Farmer: I should like to say a few words in elucidation of the points mentioned by Mr. Eckersley.

With regard to polarization error in the spaced-frame type of direction-finder, we have examined the extent to which it is present in our rotatable system by observing on waves reflected almost vertically from the ionosphere. Using a frequency which gave " split echoes " from the F region, we observed the direction of arrival of a single circularly polarized ray, first with the spaced-frame system in one position, and then after quickly turning the whole system through 180°. It is easy to see that any unwanted pick-up due to the quadrature component of the wave will appear in this case as a swing of the bearing to the opposite side of its true value, the magnitude being twice the unwanted pick-up. These tests showed that the polarization error was small compared with 0·5°.

Messrs. Barfield and Ross have given data to show the accuracy of the 4-frame direction-finder in determining absolute bearings of stations. Similar measurements have been made on the 2-frame system at Chelmsford, observing the ground wave from a transmitter at Ongar, and repeating the observations over a period of several months, and it was found that the results were consistent to about 0·1°. The true bearing also checked up with the mean of the results as closely as could be reckoned geographically. We regard these tests as evidence that the spaced-frame technique, in which the phases in two frames are compared, is capable of giving a high degree of accuracy in measured bearings.

When we come to consider downcoming waves from the ionosphere it is much more difficult to check the accuracy of a direction-finder, because of the continual variations. We have carried out measurements on Zeesen analogous to those made by Messrs. Barfield and Ross, and found variations of the order of 1° on either side of the mean, i.e. approximately the same as those shown by their curves. The value which we obtained for the mean bearing, however, agreed with the true bearing to within a fraction of a degree. We are led to suspect that the error of 2° in the mean of their results is at least partly attributable to inaccuracies in the lining-up of their frame system.

As the angle of incidence is made smaller the differences between our results and those of Messrs. Barfield and Ross seem to increase. To illustrate this we may take the transmissions from Dorchester (GLK) on a frequency of 8·0 Mc./sec., which were observed at the two places. Two independent direction-finders were employed at Chelmsford, situated 4 miles apart, one being the rotating spaced-frame system used in the tests already referred to, and the other an array of four fixed frames in which the phases in opposite members were compared. Both should be sensibly free from polarization error; the latter, however, had the advantage of determining the complete direction of arrival of the wave, so that both azimuth and angle of incidence could be computed. In typical experiments on this station the azimuth showed variations from its mean value to the extent of about 7° in either direction. The distance from Dorchester to Chelmsford is 232 km., whereas in the work of Messrs. Barfield and Ross the ground distance is only 160 km. We should expect this to increase the variations in azimuth in their case approximately in proportion to the cotangent of the angle of incidence, i.e. by about 1·5 times. It is surprising, though, to find that they observe variations in azimuth of 30° to 50°, as shown in Fig. 6 of their paper. Mr. Eckersley has drawn attention to the liability of their type of direction-finder to increased polarization error and lining-up inequality as the incidence of the wave is made steeper, and it appears that some such effects must be present to account for the differences between the observations.

On a large number of occasions simultaneous observations have been made on the two independent direction-finding systems at Chelmsford, using the transmissions from Dorchester. It is perhaps worth stressing that quite a remarkable agreement has been found between the two sets of observations: the average result of about 10 hours' observing showed a discrepancy between the two measured values of angle of incidence of less than 0·25°, while on a day of small variations in the ionosphere the two curves of angle of incidence against time have been found to be very nearly identical. Since the frames in the two systems are oriented quite differently with respect to the direction of arrival of the wave, we regard this as significant evidence that both systems are working accurately, and are not appreciably influenced by polarization effects.

During the course of ionosphere research at Chelmsford we have had occasion to make frequent measurements of the P', f characteristics of the ionosphere. Many of these curves were obtained at times when the angle of incidence of the transmissions from Dorchester was also being observed, and it is therefore of interest to see what relation exists between the two sets of observations. If we neglect the earth's magnetic field it is possible, by means of the equivalence theorem of Martyn, to calculate from the vertical-incidence P', f curve the angle at which a wave should arrive at a given receiver, for a known frequency of transmission.

On 51 occasions simultaneous P', f and angle determinations were made, and from the former the predicted angles were computed. The two were found to agree to within 0·2°, the probable error being of about this magnitude, so that we can say there is very close accord between the vertical-incidence characteristics and the angle of incidence of the given transmission. This is of interest from the point of view of direction-finding since it provides a check on the absolute accuracy of the spaced-frame system for measuring the angle of incidence of a downcoming wave: there is good reason to believe that the effect of the earth's field on the equivalence theorem for these high frequencies is very small indeed, in which case we conclude that the measured angles are accurate to a small fraction of a degree.

If this result, together with the other evidence bearing on the accuracy of the apparatus, is valid, the important conclusion is reached that the variations observed in angle of arrival of a wave are *real* variations, having their origin in the ionosphere; and that they set an irreducible limit to the accuracy of bearing that can be obtained with any type of receiving apparatus.

Mr. R. H. Harrison: The remarks which I should like to make arise in connection with the installation of a number of four-aerial Adcock systems covering wavelengths from 20 m. to 100 m. In connection with the calibration of those stations, we have adopted the suggestion put forward in Mr. Ross's paper of making calibrations at distances of the order of 200 yd. round the direction-finding equipment, and also (the method adopted before that paper was available) at distances of the order of 10 miles. The agreement between the two methods is surprisingly close, but the advantages of making the calibration at the shorter distance are many.

As regards the necessity for screening direction-finding equipment by placing it and the operator in a screened cage, I would mention that errors are liable to be introduced also by the wiring and other metalwork which has to be put in the direction-finding building. At the suggestion of Mr. Gill, we installed an underground steel tank, roughly 12 ft. in diameter and about 8 ft. high, to house the direction-finding equipment and operators. We have erected similar aerial systems to the ones we had put up in the other stations, and have found that the system is now much more simple to calibrate and the results more accurate. The new arrangement seems to promise a means of getting rid of many of the difficulties experienced when erecting these direction-finding stations in ordinary buildings.

Dr. Smith-Rose mentioned that the errors met with in using ultra-short-wave direction-finding equipment increase as the distance between the measuring equipment and the transmitter is reduced. The Post Office have made some tests on one of these direction-finding equipments in connection with the location of sources of interference. Our results confirm that there is an increase in error with reduction in distance from the source, and errors many times greater than 8° have been experienced at short distances in built-up areas.

Mr. S. B. Smith: During the past 10 years considerable experience has been accumulated of the factors involved in the problem of Adcock-direction-finder site-selection. The requirements for such direction-finder sites are far more stringent than those usually associated with sites for loop direction-finders; in fact, locations admirably suited to the latter are often quite useless for the installation of spaced-aerial direction-finders. The operating and administrative criteria usually take precedence over technical considerations, and in certain military applications the choice of site is frequently limited in scope to such an extent that lowered performance is often to be expected.

When guaranteeing the overall results upon certain sites without preliminary testing, the commercial hazards are likely to be considerable; in some cases visual inspection of the site is insufficient. A number of reasons contribute to this statement, such as: (1) The penetration depth of waves underneath poor subsoils may be very irregular, and thus the ideal flat and uniformly-conducting site is not present, despite the apparent flatness of the top soil. (2) Sources of re-radiation such as adjacent aerials, lines, buildings, etc., are not amenable, with our present knowledge, to precise engineering treatment. (3) The site may be required to provide direction-finder aids over a continuous frequency band of 0·1 to 20 Mc./sec. In such cases the site conditions and needs may even change considerably from one part of the spectrum to another. (4) Any non-level and irregular site may possess a fairly well-defined polar diagram, which is, of course, most undesirable from the point of view of the installation of the types of Adcock aerial under consideration.

The subject of the selection and preliminary testing of Adcock direction-finder sites has not received adequate attention, either by the user or by the technician. In passing, it is interesting to observe that with the continuous expansion of overland direction-finding we are slowly accumulating data relating to geographic errors, and in time it should be possible to produce charts showing areas of bad bearing in a manner akin to the marine practice of indicating arcs of good bearing.

With regard to overall accuracy as a function of site conditions, the papers dealing with short-wave and medium-wave Adcock aerials concern themselves largely with design and testing methods, and treat the subject more from the ideal-site point of view than from that of the operating engineer. In many ways the Radio Research Board may be wise in confining the work in this way; it at least gives us a treatment disconnected from some site complexities.

Sufficient field and laboratory data do exist to indicate that the purely instrumental ideal-site overall accuracy is adequate for most uses, but that the site and its vicinity, coupled with the limiting probable accuracy of the direction of arrival, place the usual limit to the probable accuracy. One frequently hears that the radiogoniometer possesses an accuracy of ± 0·1°, when the controlling factors involving the overall-error curve are usually beyond the control of such an instrument. A study of the daytime overall field accuracy attainable upon a typical series of stations compared with laboratory conditions has clearly shown that no matter how small the instrumental error may be, the average site and geography will control the final correction curve and accuracy.

With reference to polar-diagram effects due to site imperfections, the polar diagrams of each of the vertical-aerial elements are assumed to be circles. If site conditions are such that all four vertical members possess quite random azimuthal and zenithal e.m.f.'s and that after allowing for wave-spacing their phases are not correct, then clearly an efficient direction-finder will not result.

Measurements upon sites possessing well-defined polar diagrams and upon distortion-free sites have been made by various methods, and the results do not produce such a simple picture as those obtained by the author. For example, local balancing methods, using either a rigidly central radiator or a test aerial located at 45° from the plane of each aerial, are liable to grave errors when a polar diagram exists around the site. Thus in one of our experiments a complete spaced-aerial system was balanced by the central-radiator method. The calculated minima-to-maxima ratio of the resulting polar diagram for such a balance should have been 60 db., whereas a signal received upon the balance frequency from a distant station produced a ratio of 15 db. with an error of 5°. The same test carried out upon a good site produced agreement between the local and distant signals.

By means of a phase and amplitude comparator technique it was found possible to measure the phase and magnitude of the e.m.f. induced in each of the four spaced aerials and to calculate the resulting polar curve from such individual quantities; and, upon comparing the results with those observed upon the direction-finder, sufficiently close agreement resulted. These results, when compared, showed (1) identical impurities in the polar diagram as observed upon the radiogoniometer, and (2) equal errors; they also explained why the use of minima compensation upon such sites would cause the bearing to change for various quadrature-correction values, somewhat akin to the ship case.

The comparator method has been used on several types of site, and the circuit gives a complete picture of the forces which are active in the aerial system. I have used the comparator only for this analysis in the medium-wave band. It may be of interest to record that under the worst conditions the maximum inequality in azimuthal vertical amplitude amounted to 11%, with phase-angle discrepancies of approximately 1° at a wave-spacing of 40°.

The polar diagrams which seem to exist upon some medium-wave sites are much more complex than those due to a ship, and any local balancing or overall calibration methods must assume or prove the site to be distortionless, otherwise the results cannot be relied upon. This opinion has been arrived at after obtaining experience with the following: (1) central radiating vertical aerial; (2) central rotating radiating loop giving overall back-to-back test; (3) local visual rod-aerial transmitter, at suitable location; and (4) distant calibrating transmitters. It seems to me that ultimately a new technique of site testing analogous to that used by the B.B.C. when site surveying will require to be devised, to ensure that a truly distortionless location is selected.

With regard to methods used upon poorly or non-uniformly conducting sites, in some cases large radial earth systems possessing a radius of from 5 to 10 times the aerial height have been used, with improved results. Under some conditions the introduction into a site of power and control lines (even if buried underground) has introduced polar diagrams superimposed upon the normal polar diagrams of the spaced aerials. Lines loaded in such a manner that they cannot radiate at the working frequencies have been applied in special cases with some degree of success. This seems to suggest that the installation of non-radiating buried cables, in conjunction with large radial earth systems, will form one solution to some problems of difficult site location.

Referring to the paper by Messrs. Barfield and Fereday, I do not find any reference in it to stability of balance in relation to season and time. My experience has indicated that such balances are elegant, but that under service conditions they cannot be maintained with any assurance that the average performance is markedly superior to that of more simple circuits. Can the authors give us some figures on this subject?

The paper by Messrs. Barfield and Ross covers a technician's dream, namely a frequency range of 4·3 to 8·6 Mc./sec. Unfortunately, misguided users ask for a frequency range of 1·5 to 20 Mc./sec., using one aerial and instrument without any coil-changing or re-balancing, and this aspect of the matter is rather inclined to weigh heavily with the designer. For example, during the past 18 months I have worked upon a symmetrical balanced Adcock aerial with broad-band circuits, and the problems connected with it are still far from solved.

The paper by Mr. Ross closely confirms our own experience. Upon an ideal site at Chelmsford we have found source errors due to wave separation between the rod aerial and the direction-finder, when close separations have been used. Trees and other vegetation have produced transmitter source errors, and cornfield locations for the transmitter have given an effect somewhat similar in nature to scattering. Finally, ditches have been found to possess polar diagrams having frequently errors up to ± 3° within the 10- to 20-Mc./sec. bands. In several cases, either aircraft or distant-station calibrations have been the only means capable of producing effective correction curves. Cases have been recorded wherein direct-ray medium-frequency signals have shown coastal refraction errors of 4°, while short-wave reflected-signal bearings upon the same site have been correct. In the case in question, the low- and medium-frequency transmitters were also located in the same locality.

Mr. A. J. Gill: Dr. Smith-Rose mentioned that the closed-loop direction-finder was used from 1914 to 1918, during the War. The early patents of Bellini and Tosi do not relate to closed loops, however, but to open aerials. I remember in 1915 doing some work with Captain Round at Chelmsford, when he abandoned the top horizontal connection in a Bellini–Tosi system.

With regard to the use of spaced-frame direction-finders, some work was done in America by Friis in the early 'twenties, and as a result the Post Office developed that system in England for the reception of long-wave transatlantic telephony. We tried to use the long

Beverage antenna in the first instance, but owing to the high conductivity of the soil in Britain the wave had very little horizontal component, and although the Beverage antenna worked well in America, it would not work satisfactorily here.

With regard to the site-error question, it is often necessary to put up direction-finding systems at sites where transmitters are also in operation. The difficulties are great enough with the Bellini–Tosi system, but they are infinitely worse with the Adcock. We have in two or three cases — Cullercoats is one of them — put up an Adcock system, tried it out, and replaced it by the Bellini–Tosi system, because the error has been too great. Sometimes we have gone to a clear site away from any other station to couple up with transmission lines, but have met with the same difficulty: we have put up four vertical aerials, and one has given entirely different reception from the other three.

Mr. Eckersley objects to using four fixed-loop aerials. I would suggest that a more satisfactory arrangement can be achieved with a system consisting of four sets of two loops at right angles. If we put a quarter-wave-length line (or a 90° phase-shifting network) into the output from one loop of each pair and couple this output with that of the other loop by means of the normal hybrid-coil arrangement we get a summation for each pair which is omnidirectional. In this way it is possible to obtain a balanced aerial unit which is very little affected by earth and which should give quite satisfactory service in a spaced-aerial direction-finding scheme.

REPLY OF DR. SMITH-ROSE (ON BEHALF OF THE AUTHORS) TO THE DISCUSSION

Dr. R. L. Smith-Rose (*in reply*): The paper in this Symposium which has received most criticism in the discussion appears to be the one by Messrs. Barfield and Ross (No. 4) dealing with the four-aerial spaced-loop direction-finder. It is convenient to consider together the various points raised by Mr. Eckersley and Mr. Farmer.

Mr. Eckersley has endeavoured to show that what he terms "the four-poster" system must be inferior to a "two-poster" system when dealing with rays incident nearly vertically. His arguments are, however, somewhat loose, and it appears to us that his conclusions are not fully justified. In fact, it is not difficult to see that the two systems become subject to almost the same limitations as the angle of incidence decreases. Consider, for example, a two-aerial system oriented so that a wave is received at an angle of incidence θ (with the vertical), the vertical plane containing the ray making an angle ψ with the vertical plane bisecting at right angles the line joining the aerials. The phase-difference between the voltages induced in the aerials is $\frac{2\pi d}{\lambda}\sin\theta\sin\psi$, where d is the distance between the aerials and λ is the wavelength.

It is seen that this phase difference decreases with θ, in just the same way as the amplitudes which are compared in a four-aerial system decrease. It is clear that if there is any residual polarization error, or direct pick-up on the amplifier, the accuracy with which a given lateral angle ψ can be measured will decrease with θ in just the same way as for a four-aerial system, for it must be borne in mind that the phase difference is measured by moving a phase-shifting control so as to have minimum output from the receiver. The line of thought which has led Mr. Eckersley to his conclusions seems to lie in the fact that, while it is true that the "two-poster" can measure a given phase-difference between the e.m.f.'s induced in the aerials with the same accuracy whatever the angle of incidence of the received wave, the actual phase-difference produced by a given azimuthal deviation of the wave is proportional to the sine of the angle of incidence and therefore decreases with the angle of incidence. The accuracy with which azimuthal deviations can be measured, therefore, decreases as the angle of incidence decreases in almost the same manner as for a "four-poster" system.

Mr. Eckersley further makes the statement that it is almost impossible to make the four elements of a four-aerial system equal and states that, in the two-aerial system, equality of the elements is rendered unnecessary by the process of lining-up adopted. It seems to us, however, that the process of lining-up the four-aerial system by means of a centrally placed oscillator, as described in the paper by Messrs. Barfield and Ross, is almost exactly equivalent to the lining-up process adopted by Mr. Eckersley in connection with his "two-poster."

There is, however, one aspect in which the two-aerial system can be regarded as definitely superior to the four-aerial system, and this is that whereas in the former system adjustments are required to only two aerials, in the latter there are four elements to be lined up. The overall effect of this is that the residual instrumental error of the four-element system is liable to be greater than for the two-aerial system by a factor of 2 or 3. In the actual four-aerial system described a further source of instrumental error arises from the need of using two separate amplifiers for the two aerial pairs. The residual lining-up error of these amplifiers is included in the estimates of the overall instrumental accuracy given in the paper.

Mr. Eckersley doubts whether the "snapshot" technique adopted by the Radio Research Board really gives the information sought, namely the direction of arrival of the wave. It is admitted that a single snapshot may not indicate the direction of arrival of the wave, particularly if the signals received consist of several distinct rays not all in the same vertical plane. This point is dealt with on pages 104 and 105 of the paper (No. 4). It should be emphasized that the same difficulty would arise in the case of Mr. Eckersley's two-aerial system, were he in fact able to take snapshots of the instantaneous phase-difference between the aerials. Actually his phase measurements are made by means of a manually-operated phase-shifter and, as in the case of a manually-operated goniometer, some sort of averaging must take place. It is precisely the vagueness of the degree and kind of averaging which takes place in a manually-operated system that renders it inferior to a photographic recording system for scientific work. Each snapshot does yield the exact "apparent" bearing at the instant of taking. A manual bearing may indicate an instantaneous bearing or may indicate an average over several seconds depending on the skill of the operator and the character of the bearing. The only sound method of collecting data in circumstances in which the instantaneous apparent bearing fluctuates very rapidly is to collect a large number of instantaneous readings and use some logical process of selection. This has been done in the results quoted in the paper. When pulse signals are being received and the individual rays are more or less separated, it is found that the degree and rapidity of the moment-to-moment fluctuations in apparent direction of the individual rays are usually considerably less than for the case of C.W. signals; and in these circumstances a photographic technique and a manual system would yield almost identical results. Thus, although it is possibly true that each individual ray is spread over a cone, as Mr. Eckersley has suggested, the effect so far as the difference between instantaneous and average bearing is concerned is not in general large. It is only when several distinct rays are being received that one might expect much difference between an instantaneously-recording system and a manually-operated one.

With regard to the differences between the results obtained with our four-aerial spaced-loop and Mr. Eckersley's two-aerial system, it is our opinion that the magnitude of these differences has been rather exaggerated by Mr. Eckersley and Mr. Farmer. So far as distant stations, such as Zeesen, are concerned, the fact that they (Messrs. Eckersley and Farmer) have observed somewhat smaller deviations about the mean bearing than those quoted by us in the tables in our paper, is no doubt mainly explained by the difference between the photographic recording technique and the manual operation adopted in Mr. Eckersley's system. So far as the mean error of 2° is concerned, this is probably partly residual instrumental error, but is no doubt also partly due to site error. Experience with other direction-finders on the same site has clearly indicated that site errors of this magnitude are quite likely to occur.

When we come to consider the results obtained on Dorchester, both Mr. Farmer and Mr. Eckersley have laid stress on what appears to them to be a considerable discrepancy between the orders of the deviations observed by them and by us. It should be clearly stated that the value 50° so frequently quoted by them refers only to the maximum deviation ever observed by us for this station. Mr. Farmer states that in " typical experiments on this station (Dorchester), the azimuth showed deviations from its mean value to the extent of about 7°." It would be interesting to know what was the maximum deviation which they have ever observed on this station. An examination of all our results has shown that for 75 % of the time during which we have made observations on Dorchester, the deviation of the bearing from the true bearing has been less than 20°. If we were asked to quote a " typical " value for the deviations observed by us we should give 15°–20° as the most reasonable value to take. Allowing for the difference in the angles of incidence at Slough and Beddels End, the 7° deviation of Mr. Farmer's typical experiment would become about 12° for Slough. It would appear to be most reasonable to compare this value of 12° not with the maximum deviation observed by us, but with the value of 15°–20° quoted by us.

It is interesting to know that Mr. Cox has been making calculations of an analogous nature to those made by Mr. Ross on the errors introduced by proximity of the calibrating transmitter. His problem, however, has been somewhat simpler than the one attempted by Mr. Ross, and he has been able to supply a correction formula to apply to cases of nearby calibration. In the case of a four-aerial system, however, Mr. Ross has shown that the errors introduced by proximity of the calibrating transmitter are a function of the residual instrumental errors of the direction-finder, and no entirely general correcting curve could be given by which nearby calibrations could be corrected which would apply to all direction-finders. If the residual instrumental errors due to aerial misbalance were known, it would be possible, from the results given in the paper, to correct calibrations made at very close range so that they would apply to long range.

The agreement found by Mr. Harrison between close-range and long-range calibrations is of interest and indicates the results which may be obtained when site error and lateral deviation of the ground ray are absent. Unfortunately, it will frequently be found that very long-range calibrations do not agree with calibrations made at close ranges, on account of these two factors.

Mr. Smith's contribution to the discussion is of great value in bringing out only too clearly many of the practical problems met with in direction-finding. As he points out, it is fundamental, in the design of a spaced-aerial direction-finder, that the four aerials have exactly similar polar diagrams. Compensation can be made if they do not all have the same effective height, but no compensation is possible where the individual polar diagrams are not exactly similar. If it is found that they are not similar, then, as Mr. Smith points out, local oscillator tests may yield misleading results. This does not, however, in the majority of cases minimize the importance or usefulness of such local-oscillator tests as are described in the papers comprising the Symposium. It seems clear that, when local site conditions are so bad that four spaced aerials do not have similar polar diagrams, no direction-finding system with earth-bound aerials (i.e. either earthed aerials as in coupled systems, or aerials erected on the ground as in the Marconi-U system) will ever function satisfactorily as a direction-finder. It would appear that the effect of locally improving the properties of the site by a system of earth screens or extended earth-wires under such adverse conditions is worthy of further investigation. It is also probable that fairly compact elevated aerial systems might yield satisfactory results in such cases.

As to the question of maintaining stability of balance of the four aerials of the medium-wave Adcock direction-finder described in the paper by Messrs. Barfield and Ross, it may be stated that a station of this type has now been in practical operation for service purposes for over 2 years, and has so far shown no signs of deterioration in this respect.

Mr. Smith describes the range 4·3–8·6 Mc./sec. covered by the Radio Research Board short-wave Adcock as a " technician's dream," and goes on to quote the requirements of "misguided users." It is perhaps a controversial point as to whether a user should continue to ask for what he is told is technically impossible and thereby hope to stimulate development; but there appears to be little doubt that many of the exacting and uneconomical demands made on technicians are partly, at least, due to the absence of definite guidance from the technicians and experts themselves. Apart, however, from whether or not the range 4·3–8·6 Mc./sec. is a "technician's dream," it is surely no criticism of the Radio Research Board's work that the experimental work should be confined to restricted ranges, if it is expedient to do so. It has been generally admitted that the Board ought to confine itself to the investigation of fundamental and general principles, leaving the more technical side of development to the user or his suppliers, although complaints are occasionally made that the fundamental work is not taken sufficiently far for those responsible for development to carry it forward.

With regard to Mr. Gill's suggestion of a spaced-loop direction-finder consisting of four pairs of crossed loops, it is perhaps important to point out that, in fact, when receiving ionospheric rays the four-loop system does not, in general, possess a blind spot, as would be the case for a vertically polarized direct ray. These ionospheric rays have generally a very variable state of polarization and a single loop will not generally possess a steady minimum or zero position, as is well known to any who have attempted to use ordinary loop direction-finders on short waves at long ranges.

RADIO IN AVIATION: A GENERAL SURVEY, WITH SPECIAL REFERENCE TO THE ROYAL AIR FORCE

By N. F. S. HECHT, Member.*

(*Paper first received* 16*th June*, 1938, *and in revised form* 3*rd February*, 1939; *read before the* WIRELESS SECTION 5*th April*, 1939.)

SUMMARY

The paper discusses the conditions peculiar to aircraft operation in respect of radio-telegraphy and radio-telephony. Particular stress is given to those conditions not usually met with in other applications of radio-communication and especially to the sources of interference to reception and of danger to the aircraft and its occupants.

It concludes with a brief reference to a few special applications of radio in aviation, and while no attempt is made to describe the equipment itself the fundamental principles on which its construction is based are briefly given.

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INTRODUCTION

The present paper is not intended to give quantitative information on the extremely varied and technically complex devices provided by the engineer in the establishment, improvement, and extension of the radio-communication services required by aviation. Rather is it intended to convey, to those interested in the requirements of the air services, the many difficulties the engineer has had to overcome and that are still confronting him in order that he may supply to aviation a comprehensive and reliable service.

An attempt will be made to touch upon every branch of radio-communication playing a direct part in the equipment of aeroplanes and of specialized equipment on the ground in connection with aviation problems. This, perhaps rather ambitious, proposal necessarily entails the exclusion of all reference to radio-communication equipment developed for commercial purposes and applied to the air services without involving specialized study or design.

It will be appreciated that in a general survey such as this it is impracticable to refer to individual workers and authors who have contributed to the evolution of the art. For the same reason it is not proposed to give a bibliography of the subject; such a bibliography would be either cumbersome or grossly incomplete.

Finally, it should be stated that the methods, processes, and designs to which attention is called in this paper, are due to the efforts of workers in all countries; wherever possible, outstanding departures from current practice will be credited to the originating country or individual.

PART I

GENERAL AVIATION PROBLEMS

The problems which are quite general to aviation, both civil and military, can be stated as follows: It is required to transmit intelligence from and to the aircraft by means of telegraphy or telephony. Although no peculiar difficulties arise in the case of the ground installation, the aircraft problem is rendered a difficult one by the fact that it is impossible to provide an aerial which shall be equally efficient in all directions, that the power available is strictly limited, that bulk and weight are most important considerations, and that operating conditions are very far from normal. The conditions and inherent difficulties and limitations will now be considered in detail.

(1) Aerials

(a) Long and medium waves.

In the early days of radio-communication in aviation, aircraft were relatively slow, and it was possible to pay out a considerable length of wire, suitably weighted at its end, and ensure that the effective height was a relatively high proportion of the available length. Wire, usually made of copper but sometimes of bronze and similar alloys and nowadays frequently made of stainless steel, was let out by means of a reel fitted in the fuselage at a convenient distance from the operator's hand.

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* Air Ministry.

Lengths of 200 to 300 ft. were commonly employed and were terminated by lead weights of the order of 1 lb. for ordinary aircraft and of 2 to 3 lb. for flying boats, with substantially increased wire diameter.* It was a reasonably easy matter to pay out the aerial or to reel it in. For this purpose the reel was designed to be operated by means of a handle which could be in one of three states: Locked for use, free on a ratchet for winding in, and free but with adjustable braking action for control during paying out. This class of winch is still in use and is fitted with a clamp, usually spring-loaded, whereby the wire can be held securely, thus providing a good contact, an essential point during reception.

The types of weight used for the terminal bob varied in different countries and included solid weights secured on a spring, finned weights to increase downward pull on the aerial, and distributed weights to reduce a snatching action which will be referred to later. The aerial wire was originally let through the floor of the fuselage through a fairlead of insulating material, the weight in the wound-in position being flush with its lower end.

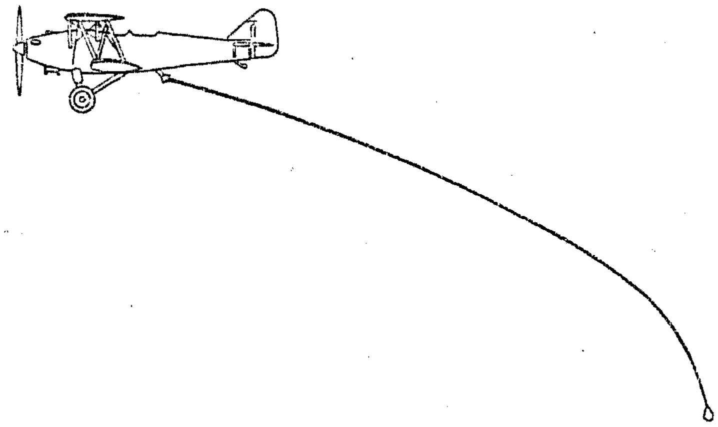

Fig. 1.—Aerial in flight.

The form taken by the aerial on an aeroplane in flight is shown in Fig. 1, from which it will be seen that the angle of trail of a wire increases as the length is reduced. The general shape of the curved portion is the same for all lengths and depends upon the diameter and smoothness of the wire, its weight, and the drag and weight of the terminal bob. Thus shorter aerials have a greater effective-height factor than long ones. Now from the fact that the wire trails at a small angle to the horizontal it will be appreciated that a considerable side load is applied to the end of the fairlead; this can be roughly represented as equal to $W \cot \theta$, where W is the weight of the bob and wire and θ is the trailing angle. This condition would cause serious wear at the end of the fairlead as the wire was paid out or reeled in and also during its oscillations in flight; consequently it has been usual to fit to the end of the fairlead a hardened-steel flare or ring and so reduce wear. Now, owing to turbulent motion of the air in the neighbourhood of the wire, generated by the propeller and by the aircraft in general, the aerial does not hang steadily along the ideal curve. It oscillates both in the vertical plane and in the horizontal direction; also, for some reason which, as far as the author is aware, has not been completely determined, the weight spins more or less continuously on its axis and not infrequently this tendency to spin is more marked in a left-handed screw direction than in the reverse sense. Since stranded wires are usually laid in right-handed fashion the result was that the wires were frequently twisted more and more tightly. This effect, combined with kinks due to the oscillations of the bob, caused frequent breakages of the aerial, such breakages being usually localized near the weight. In order to overcome this defect it has been common practice to mount the weight or bob on a swivel, thus giving it complete freedom of rotation.

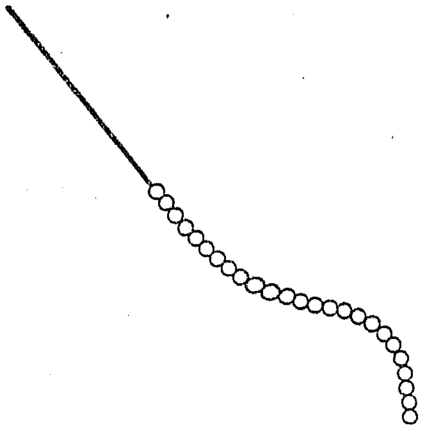

Fig. 2.—Bead aerial in flight.

Nevertheless, fractures were still frequent. Investigations made by means of a ciné-camera showed that the bob frequently made deep dives and lurches, ending with a sharp snatch on the wire when it reached its extreme position. The kinetic energy of the bob suddenly dissipated in the wire was apparently the cause of the fractures experienced. One way of overcoming this effect was to break up the weight into a number of small units strung in a chain on a steel cable. The movement of this " bead " aerial, as it has been called, is not essentially different from that of the single weight, but, owing to the fact that the complete aerial weight is usually not extended in a straight line, but more as shown in Fig. 2, each bead is decelerated in turn, thus considerably reducing the snatch on the wire. This form of aerial has been found very much more satisfactory.

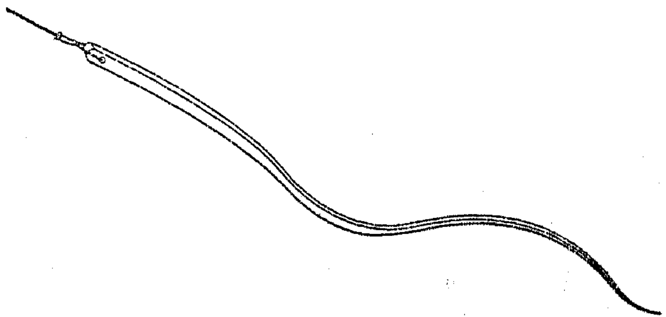

Fig. 3.—American weight in flight.

A derivative of this type of weight was recently introduced in the United States, where it was given the form shown in Fig. 3. The beads are here replaced by a continuous length of pliable rubber gradually tapering towards the end, which acts partly as a weight and partly as a stabilizer.

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* The latter has been discontinued and the normal size is now fitted.

A type of aerial weight which appears to have met with some success in America and in Germany is the finned streamlined weight, sometimes known as a " fish." The idea is that the weight shall fly under the stabilizing influence of the fins. It has also been proposed to give the horizontal fins such a shape as to cause a downward pressure in flight, thus adding to the effective weight of the bob without increasing its drag. It is found, however, that this class of weight is not entirely satisfactory in flight and occasionally swoops dangerously in the vertical plane. At any rate, the author's experience of it has been disappointing, and it is thought that at high aircraft speeds the device is a positive danger in all but perfectly level and smooth flying.

In view of the fractures of the aerial wire which are liable to occur, fairlead designs have been modified to allow of the slipping-out of a complete aerial and weight through the fairlead. This is a very difficult matter with roughly spherical and solid weights, but quite simple when the bead construction is used. The beads can be let down along the fairlead from the open upper end or can be inserted through an aperture in its side where it projects into the fuselage. Sometimes this opening is continued to the top by a narrow slit just wide enough to allow the wire to slip through. This facilitates the insertion of new aerials when the upper end of the fairlead is rather close to the reel or winch.

In general, fairleads are permanent fixtures in the aircraft where they are installed with a slight trail to reduce stresses in the material. It would seem at first sight that the trail angle of the fairlead should be equal to that of the aerial in normal flight, but this condition is not permissible on account of the difficulty of paying out when the weight is within the fairlead and therefore out of the slip-stream. This difficulty is intensified when long lead-down tubes are used, as is often the case in large aircraft.

In the case of flying boats the fairlead becomes a particularly difficult item of design and installation, since it has to be of rather greater length than usual and must be watertight for use on the water. The general practice is to provide a tube inside the hull with its lower end rendered watertight where it joins the hull. Before landing, the aerial and fairlead are withdrawn from the protective tube, which is then sealed at its upper end to prevent the ingress of water.

The insulation of the fairlead from the structure of the aircraft is a matter which calls for special care. Adequate leakage path has to be provided between the tube and the metallic " dope " or metal skin of the aircraft. In addition to the substantial insulator used it is usual to leave a patch, about 1 sq. ft. in area, free from metallic dope in order to avoid causing severe stress on the surrounding coating, which is a semiconductor of high-frequency currents.

The process of winding-in the aerial becomes a matter of pronounced physical exertion in the case of high-speed aircraft, and especially so when the operator has remained at high altitudes for some time and has required the use of oxygen. It frequently takes as long as 5 or 6 minutes for the operator to wind-in 250 ft. of wire, with occasional intervals for rest. Designers have therefore been busy for years devising automatic power-driven winches, but it can hardly be said that these have been received with favour. There are no very substantial reasons for this failure, but perhaps the weight involved and the power consumption, derived from the aircraft's accumulator, are the chief obstacles. Wind-driven winches have also been suggested and tried out, but as far as the author is aware they have not been applied in practice.

It is important that as great a vertical component as possible should be given to the aerial wire, in order that the intensity of the vertically polarized field shall be as great as possible. Horizontal polarization causes restriction of communication in certain directions, notably when the aeroplane is tail-on to the ground station. But there is a further reason for keeping the trail angle as large as possible with respect to the horizontal, and that is the needs of direction-finding (see Part II).

With the high-speed aircraft of the present day the trailing aerial has become a very serious problem, both to the designer of the aircraft and to the radio engineer. Trail angles have become extremely small, thus causing a risk of fouling the aircraft structure and causing also a very serious reduction of range of communication.

(b) Short waves.

This has driven the radio engineer more and more towards the use of fixed aerials. With these it is impracticable to provide an effective height of more than a few feet or so, except in very large transport aircraft; in the case of small aircraft the effective height is limited to little more than 18 to 24 in. Under these conditions it will be appreciated that long or even medium waves are no longer utilizable with any useful degree of efficiency. Nevertheless, on larger aircraft a fixed aerial above the aeroplane is employed even for long- and medium-wave communication over short distances and, in the case of flying boats, when the aircraft is down on the water. On account of the small electric capacitance of these fixed aerials the radio apparatus has to be loaded with inductance or capacitance, both of which cause a serious reduction of aerial current and hence of range.

The fixed aerial is a problem in itself, whether it is located below or above the fuselage. It becomes a particularly difficult one in the case of military aircraft. In the upper position it is liable to be in the line of gunfire, and in the underneath position it has to be clear of bomb racks and torpedoes and of retractable undercarriages. Both types have been employed, and in the case of the underneath aerial it has usually been found necessary to provide retractable gear to allow the aircraft to run along the ground, possibly in long grass, without risk of the aerial being torn away. As regards aerials in the upper position, it has always been a matter of compromise between the radio requirements and the aeronautical design.

The most general forms employed are shown in Fig. 4, where A represents a wing-tip-to-tail aerial, B a fore-and-aft single wire, C the broad-arrow type, and D the Y type. Each has its particular points. For instance, the wing-tip-to-tail type is a better radiator but it suffers from drag at high speeds and instability in the slip-stream; it is also a hazard when, in emergency, the occupants of the aircraft have to have recourse to their parachutes. It is also liable to be shot away by the gun, when it constitutes a further hazard should it become entangled in the tail and rudder or in the elevator. The fore-and-aft type is more stable but is less efficient. It is perhaps a little less liable to be shot away, causes less drag, and is less dangerous from the point of view of parachute descents. The broad-arrow type is inefficient owing to the close proximity of its lower member to the metal structure of the aircraft. It is safer, however, from the point of view of gunfire since the joint is in a position through which the gun is not permitted to fire. The Y type is more efficient owing to its direct vertical limb, but its electric capacitance is small. It has the advantage of electrical symmetry, which improves conditions for direction-finding purposes.

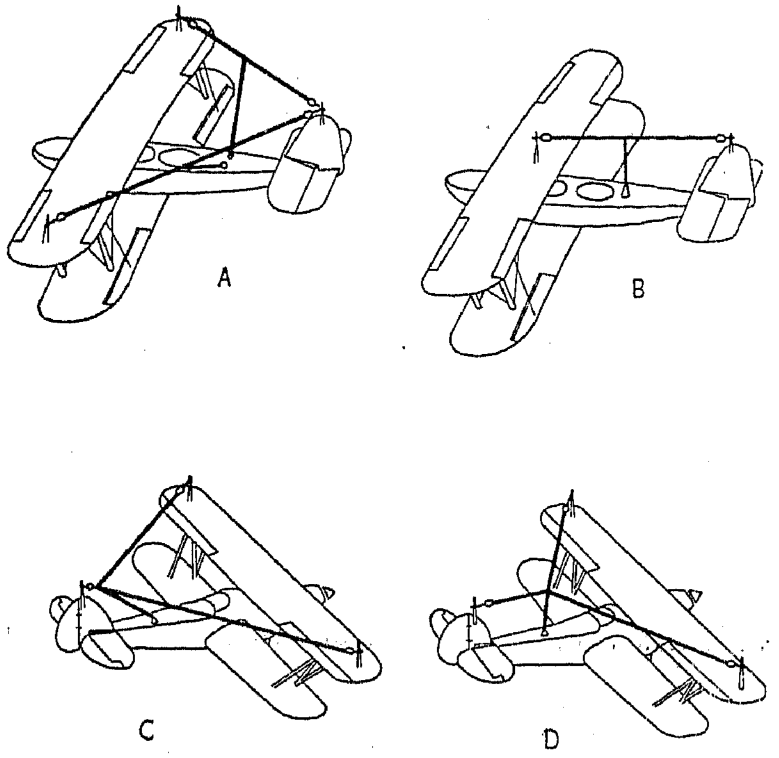

Fig. 4.—R.A.F. aerials.

In recent years the demand that flying boats should have greater reliability over long distances has given rise to an improved technique in short-wave fixed-aerial design. Whereas it had been the practice to tune the aerial as part of the transmitter or receiver circuit, the increasing size of aircraft and the attendant installation difficulties occasioned heavy current losses in the feeder. Modern practice utilizes elevated dipoles joined to a transmission line through a matching transformer and another matching transformer at the apparatus end. This practice should ensure a much improved aerial and set efficiency, but it is too early to give any figure for the improvement in terms of range and reliability. It will be observed that this technique, new for aircraft installations, seriously curtails the flexibility of the system. It is necessary to provide separate transformers or transformer taps for different wave-bands, and to provide remote control for the outer transformer, which is located as near to the aerial as possible.

A typical arrangement is shown in Fig. 5. This aerial system can be used on medium waves with fair efficiency by connecting the dipoles as the two limbs of a T aerial, the feeders being then parallel vertical radiators. On short waves the dipoles radiate horizontally-polarized waves, and since long-range transmission involves ionized-layer reflections the radiators are effective even when the aircraft flies at right angles to the great circle of the ground station and aircraft.

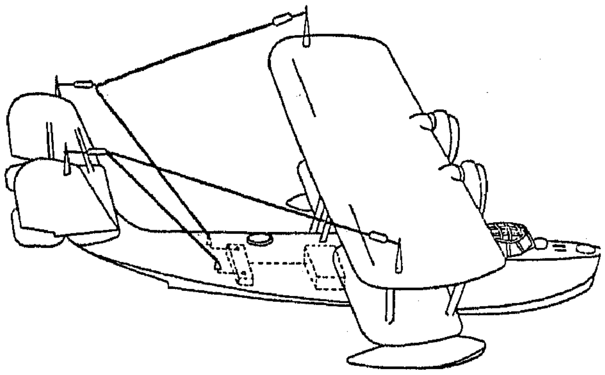

Fig. 5.—Fed aerials.

Aerials require to be carefully insulated from the structure of the aircraft, and must also be resiliently mounted. The usual practice is to terminate the upper wires with a length of shock absorber fastened at one end to the structure and at the other to the aerial wire through an insulator. In order that drag shall not be excessive the insulator has to be reduced to the smallest dimensions compatible with adequate mechanical strength. This insulator may be made in a considerable variety of forms, and Fig. 6 shows a typical example used in England.

The need for stability demands that the wires shall be kept as taut as possible, but on the other hand this tautness is restricted by conditions of design of the aircraft itself which do not tolerate excessive stresses, especially if there is any tendency for them to become unbalanced. Consequently it is usual to find that these aerials are subject to considerable vibration, the effects of which will be examined in another Section.

The lead-in insulator does not raise any special problems; the stresses on it are small, and it causes little drag in view of its small dimensions.

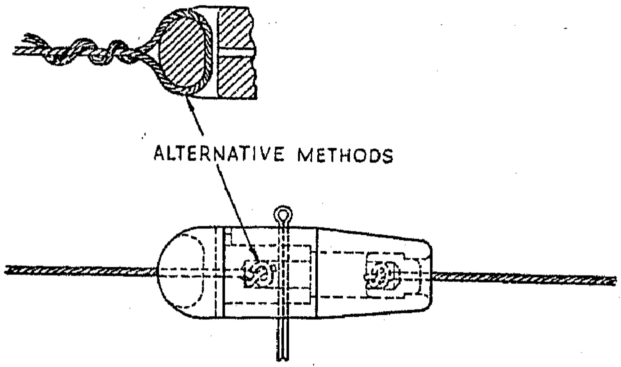

Fig. 6.—Insulator acorn.

But the design of insulators, fairleads, and lead-in devices is complicated by a relatively new factor, namely the formation of ice at high speeds and in an atmosphere of appropriate humidity and temperature. The conditions for ice formation are very restricted in respect of temperature and humidity. The former condition in particular is generally limited to a few degrees above and below zero Centigrade. Nevertheless, when such conditions are encountered ice is formed and, besides its effect on the aircraft in general, such ice formation is responsible for two defects. First, on the aerial wire there may accumulate a heavy layer of ice which by virtue of increased drag may cause the wire to break. Secondly, the insulators become covered over and may cause sufficient losses to interfere seriously both with reception and with transmission. It may be that the efficiency of the transmitter is very considerably reduced, or in other cases that the tuning of the circuits is sufficiently altered to cause a change in the frequency emitted and occasion faulty reception of signals.

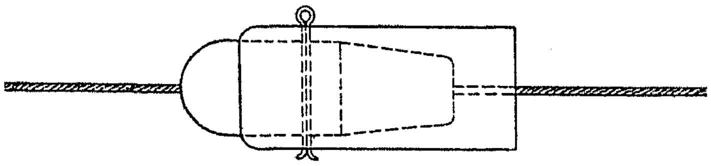

Fig. 7.—Insulator acorn, with shroud.

The worst offender in this respect is the strain insulator of Fig. 6. The effect due to ice-accretion on this component has been eliminated by fitting a skirt extending beyond the insulator (see Fig. 7); this skirt remains free from ice on its internal surface, and leakage or short-circuiting is thus eliminated.

Protection for the lead-in or deck insulator can be provided by the simple expedient of partly enclosing it in a cowl on the leading side; this cowl, which may be of metal, collects ice but prevents its accretion on the deck insulator itself (see Fig. 8).

The fairlead for the trailing aerial is a more difficult matter, as it is impracticable to fit a baffle along the whole of its length and particularly at its extremity. Such a baffle would produce a heavy drag, which would demand further strengthening of the tube with consequent increase in drag. One way which has been suggested for overcoming the difficulty is to make the whole fairlead of metal and to rely on adequate insulation at the point of attachment to the fuselage. It is then permissible to fit a short baffle in front of the insulator, and as this baffle may be supported directly from the fuselage it imposes no increase in drag and consequent stresses to the tube.

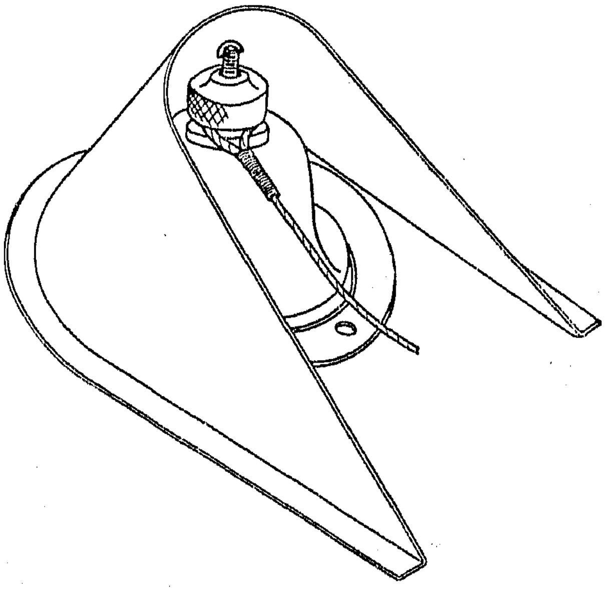

Fig. 8.—Shielded lead-in.

Apart from the skirted strain insulator it is not thought that these measures have yet been applied extensively.

(2) Earths

The subject of aerials is intimately linked with that of the earth system on the aircraft. In the early days of wooden aircraft the aerial was balanced by means of a counterpoise which consisted of a network of insulated wires supported inside the fuselage and wings. The larger masses of metalwork in the aircraft, engine, tanks, etc., were brought in to the counterpoise system by means of bonding wires and so started the thorough bonding system which is now so familiar to aircraft constructors. This subject will receive separate treatment in the next Section.

With the advent of all-metal aircraft the usefulness of the counterpoise, which can now take the name of " earth," increased very considerably, and it was possible to dispense completely with supplementary earth-wires. But this improvement was not an unmixed blessing, for, on short waves, it was found that with the apparatus then current the counterpoise could not be treated as a simple capacitance. Its dimensions were such as to cause prohibitive impedance, and on certain frequencies the oscillating system was so far mismatched that the efficiency was extremely low. With a self-oscillating direct-coupled system it was frequently impossible to maintain oscillations over the whole of the required wave-band. Various ways of overcoming this were tried; these included small insulated counterpoises, which were brought into use over the critical wave-bands, and alternatively series condensers to reduce the coupling to the aircraft earth. This latter system was electrically satisfactory but it brought in its own troubles, as will be seen in the Section dealing with " Electric Shock."

The problem of providing a satisfactory " earth " on aircraft, quite apart from its mechanical difficulties, is a serious one. The impedance of the system varies with frequency between very wide limits, and under no conditions can it be safely regarded as having the distributed inductance and capacitance of an infinite surface. No doubt, good adjustments can be provided in the aerial-circuit-earth system such as to bring about efficient conditions, but such adjustments have to be varied with substantial changes of wavelength, thus occasioning design and operational complications. Further reference to the earth system will be made later in the paper.

(3) Bonding

Bonding may be said to have made its first appearance in aircraft when the counterpoise system was augmented by the addition of the engine, tanks, and other large masses of metal, with the object of increasing the electrical capacitance of the earth or counterpoise. But its development to its present state of thoroughness has been due to two other causes. In the first place, it was decided to bond together and to earth all lengths of wire and extensive pieces of metal, in order to eliminate the possibility of the occurrence of large potentials between parts and so reduce the fire risk arising from sparking. This condition had been found to arise in aircraft fitted with powerful transmitters operating on a wavelength of about 12 metres generated by a valve circuit taking 2 kW at an anode supply of 5 000 volts. In the second place, the introduction of high-gain receivers of the superheterodyne type in which the aerial circuit was in an oscillating condition had resulted in a severe form of interference due to a number of causes. The most fruitful source of noise was the existence of bad contacts between rubbing parts, such as cross-over points in the straining wires and cables and between control cables and their guiding tubes and supports.

Bonding noises in the fuselage structure and in the control wires were eliminated by a comprehensive system of bonding by means of which all parts in sliding contact were connected together by a bridge piece or short loop of copper wire securely attached and soldered across the contact. In other cases, where bonding was not permissible on account of the extent of the relative motion of the parts concerned, recourse was had to the provision of good and permanent insulation. Cross-over points in landing and flying wires were separated by means of insulating acorns or discs, which prevented the wires coming into accidental contact with one another.

This bonding requirement was a source of considerable trouble and expense both during erection and in maintenance. Efforts were constantly being made on all sides to reduce the very great number of points affected, but, except as regards the bonding of very small parts such as bolts and small brackets, complete bonding had to be insisted upon. Even under those conditions it was generally found that at the end of 2–3 months in service it was necessary to overhaul the aircraft to repair faults in parts not accessible during ordinary maintenance.

The advent of all-metal construction, far from simplifying the problem, made it more acute, for it was found that tubular joints were frequently electrically unsatisfactory when new, and almost invariably became very bad after a period in service. The chief trouble was the presence of enamel on surfaces in mechanical contact, which even with careful cleaning still occasioned poor electrical contacts. The defect was finally cured by the simple process of leaving the enamel on the surfaces and of providing sharp points on one of the members whereby the enamel was perforated during assembly and a good contact secured.

To avoid the fire risk which might arise through brushing or sparking at the metallic nipples of wire-reinforced petrol tubing, a special form of bonding was devised; this consisted of a single length of wire laid during manufacture under the reinforcing helix surrounding the tubing proper. This wire was securely bonded or soldered at each end where it was joined to the metallic nipples. All these features remain to the present day where they are appropriate. In wooden machines the complete bonded system is connected to the main earth strip at frequent intervals.

Although the cure for contact noises is to bond all parts together and connect them to the earth system, there remained at one time one source of noise which could not be located but which was traced quite accidentally. When oscillating aerial circuits were common, such as in the early forms of superheterodyne receivers, it was frequently found that a continuous noise occurred in flight, reminiscent of bad commutation. Careful attention to the commutator produced no improvement and the noise remained when the generator, which was fixed on the wing, was disconnected and therefore not excited. While work was being done on the aircraft on the ground to search for the cause, the windmill, which was of course stationary, was accidentally moved and the elusive noise reappeared. The cause was the rubbing contact between the commutator and brushes, the noise being independent of speed and of the voltage generated. Insulating the generator from earth only afforded a partial cure, and it was necessary for some time to add a remote-controlled brake to the windmill so that it could be stopped during reception. This state of affairs disappeared with the introduction of non-oscillating aerials for receivers.

(4) Power Supply

There are three types of power supply to be considered, namely H.T. for the transmitter, L.T. for filaments, and H.T. supply for the receiver. It is not proposed to go back to the period of spark transmitters, although this class of apparatus was quite interesting in itself, especially in view of the small amount of data then available and the very sketchy rule-of-thumb technique that was applied to aviation radio-communication problems. Reference will therefore be made to valve-type apparatus only.

(a) Transmitter H.T.

The earliest form of supply for the transmitter valve anodes was the air-driven-generator type. Direct-current generators of light weight and high rating were designed for use in the conditions of excellent cooling obtained in the slip-stream. These generators were mounted either on the wing, where they remained permanently in the slip-stream, or on the side of the fuselage, by means of a retractable bracket. The latter form enabled the operator to rotate the generator on a vertical axis, at the same time pushing it into stronger winds so as to increase the torque on the windmill; by this means he was able to regulate the speed of the generator and thus had a certain measure of control over the output voltages. This, together with the input current, was measured by means of a control box comprising an electrostatic voltmeter, to which was later added a field regulator for finer control.

The windmills used were a constant source of trouble from the point of view of speed constancy. From the earliest days, therefore, attempts have been made to produce speed regulators which would be automatic in action. One of the earliest forms, originated in France, was a windmill comprising a single blade capable of rotation on its axis and opposed by a pair of weights not in the same plane of rotation. Centrifugal force produced in the weights caused the complete blade to rotate on its axis against a spring of suitable characteristics, thus providing an isochronous governing action through automatic adaptation of the pitch to the air-speed. This type of governor was fairly successful but was not capable of accurate mechanical and aerodynamic balance at all speeds. Although it was never much used on British aeroplanes it was highly favoured in France where, it is believed, it is still occasionally used at the present day.

An improved type came from America; it was based on the same principle of balancing a centrifugal force against a spring, but an attempt had been made to keep it mechanically balanced by providing two blades. It was extensively used in the U.S.A. but never found favour in England. It was not capable of perfect aerodynamic balance and its drag was considerable owing to the size of the governor mechanism. It was followed by a much improved version of British origin in which the governor mechanism was of considerably reduced dimensions. Its action was excellent, although aerodynamic balance was still limited to a certain range of speed. It is still in use at the present day where air-driven generators are employed.

A form of governor which gave very good results was of the friction-drive type. A clutch operated from the armature end was incorporated in the drive between the windmill and the generator. This clutch was designed to release its pressure by centrifugal action, as the speed of rotation reached a certain figure. With slight increase of generator speed the pressure fell off very rapidly, thus allowing slip to take place and so preventing a further increase. It was capable of dealing with a windmill speed ratio of about 2 : 1 (2 400–4 500 r.p.m.), with a transmitted speed-change of only 20 r.p.m. in 2 400 when in proper adjustment.

Other forms of regulation were provided by means of contacting or relay devices acting on the field of the generator. Apart from their special features associated with aircraft designs, these regulators were of normal type. There were also other forms such as self-regulating machines deriving their regulation from a floating battery and compound fields, and such machines gave very satisfactory results.

But whereas fair regulation is sufficient for H.T. supplies, much greater constancy was found essential for the filament supplies provided by double-purpose generators, and it is perhaps this requirement which was instrumental in causing such careful attention to be paid to speed constancy.

In recent years the aerodynamic objections to air-driven generators have caused engineers to concentrate on the use of motor-generators or dynamotors driven directly from the central battery on the aircraft. This class of power supply offers many advantages, but the disadvantages should not be lightly set aside. In general the regulation of these machines is poor and is insufficient to permit of their being used for L.T. supply for filaments, which must therefore be derived either directly from the central battery or from a separate battery (of which more will be said later). In the case of the central battery the L.T. supply suffers from voltage variations as the various loads are switched on throughout the aircraft.

It is of course well known that variations of H.T. supply cause variations of transmitter frequency, and when C.W. is employed these variations cause unpleasant keying chirps which may be very disturbing to the receiving operator on the ground. This point will be discussed later in the paper.

(b) Transmitter and receiver L.T.

Until recent times it has been the practice to employ accumulators for supplying filament heating both for the transmitter and for the receiver. This has ensured a steady emission from the filaments with only a gradual falling-off with time. A great deal of study has been devoted by battery manufacturers to obtaining a maximum ampere-hour rating with minimum weight and bulk. A special feature which arose from the use of batteries in aircraft is the provision of non-spill devices. Some of these are very simple and take the form of special vents which allow gases to escape but which, when inverted, retain the electrolyte. In other types the battery container is made sufficiently tall to allow the electrolyte to fill the upper portion when the battery is inverted, without allowing it to reach the level of the vent, which projects well down into the container. There are many intricate designs of passing interest, but in general it can be said that the reversible-vent type is the one most widely utilized.

In recent times there has been a pronounced tendency to discard accumulators and to substitute a low-voltage winding on the motor-generator. This arrangement, however, is not of universal application, for, on an unbalanced keying-load, filament fluctuations arise which cannot always be tolerated.

(c) Receiver H.T. and grid bias.

This supply has perhaps been the cause of more trouble than anything else in connection with power supply. The necessity for a perfectly smooth voltage has, from the earliest days, established the use of dry batteries. These, however, have been troublesome owing to their poor performance and life and also on account of their bulk and weight. Their storage characteristics were originally indifferent to definitely bad in tropical climates, and would warrant a thorough and independent treatment. A great deal of work has been done by battery manufacturers to produce improved cells, which in their "inert" form have been fairly successful. These, as is well known, are perfectly dry cells which are moistened only when about to be put into service. A great deal remains to be done in this direction from the point of view of storage.

Of recent years a determined effort has been made to do away with these dry cells by arranging the provision of a separate output from the generator. This has been rendered possible by improved design of the generator windings and commutation, with consequent considerable reduction in generator ripple.

It has been suggested at various times and in various quarters that the whole question of power supply could be considerably simplified by making use of alternating current. The question has received considerable attention in various countries and particularly in the U.S.A., but so far nothing much has been done towards applying this mode of supply. The introduction of separately heated cathodes has perhaps simplified the problem somewhat, but it still remains essentially only a proposal. Factors mitigating against the use of alternating current are those relative to transformation, regulation, and smoothing. The latter point in particular involves such an increase of weight in the form of smoothing chokes and condensers as to warrant a retention of the d.c. form of supply. But it can be confidently expected that within the next few years alternating current will make its practical appearance in aircraft radio-communication equipment, and within a very short period it may well render other forms obsolete.

A point worthy of mention in connection with the battery-driven generator is the fact that power is available when the aircraft is at rest on the ground or on the water. But it may be useful to utter a word of warning. When the engines are not running and the central battery is not on charge the voltage of the latter is low and the generated frequency may be seriously off its allotted value. Further, in the case of a forced landing, it is not unusual to find that the battery is discharged flat in attempting to restart the engines. The safer, but not popular, way is to provide a special battery for use in connection with the radio-communication equipment only.

Battery-driven generators are frequently fitted with interrupter discs for I.C.W. transmission and other purposes. This fact adds importance to the question of speed constancy, especially for military purposes, where the exact value of the interruption frequency is a matter of considerable importance. Another form of power supply, which is not yet fitted as a regular practice, is the d.c. vibrator-rectifier type. Of recent years this class of power supply has received considerable attention in connection with broadcast reception and the like. It would not be strictly true to say that it is completely reliable, but it has made considerable progress. Perhaps its chief objection in connection with aircraft use is the difficulty of reducing vibrator spark disturbances to a sufficiently low level to enable weak signals to be received without interference. Its compactness and other properties make it worthy of careful consideration for the future.

(5) Range of Communications

The range requirements for the aeronautical services vary considerably. They may extend the full length of the course flown or they may be limited to half the course or even to a small fraction. There are, for instance, the short-distance services which are met with on European lines, the long-distance flights of transoceanic services, and the short ranges of certain military and naval aircraft.

This variety of ranges has brought about the use of a gradually widening band of radio frequencies. In the early days all aircraft communications were made on long and medium waves up to frequencies not exceeding 700 kc./sec.; the ranges required did not normally exceed 100 miles or so, and for these ranges medium waves and trailing aerials were quite satisfactory. As aviation developed, these wavelengths failed to provide adequate signal strength, and attention was turned towards the use of short waves. It was already known, however, that short waves, which were fairly reliable for distances less than 70 miles or so and for distances in excess of 300 miles up to several thousand miles, were quite unreliable for use over the skip zone, which can be roughly estimated for the present purpose as ranging from 100 to 300 miles. Consequently it was found necessary to provide two wave-bands; one, the medium wave-band, for use on the first part of the journey, and the other for use from 200 miles onwards. This provision called for the use of two aerials and means for changing over from one to the other. One particular type, utilized in the R.A.F. over a certain period but now abandoned, took the form of a compound trailing wire. This consisted of two trailing wires, end to end, with a length of insulating cord between them; one was of the full length of 200 ft. for use on the medium waves, while the other, for the short waves, had a length of 30 ft. and so was very much more efficient than the fixed type. It would have been best to make the short aerial the lower one, so that when the long one was wound in the remaining wire would be unaffected by possible resonances in the 200-ft. length; this, however, entailed a considerable loss of time in winding in and out to change over from short to long waves, and the reverse arrangement was adopted. It has now been replaced by the provision of a fixed aerial and a trailing aerial to meet the need of rapid wave-change. In some cases it is necessary to utilize several short waves at various times of day and night and at varying distances.

In the case of military aircraft, and particularly of fighters and others intended at certain times to fly in formation, the question of range of communications is a rather peculiar one. The occupants of the several aircraft may be required to communicate with each other by means of radio-telephony when the formation is flying wing-tip to wing-tip, i.e. at a range of a few yards. At any instant the leader of the formation may be called from the ground station, situated perhaps 100 miles away. Alternatively, the aircraft may separate to distances of many miles. Under these conditions it will be appreciated that automatic volume control* is an insufficient means of maintaining relatively constant output. For this reason hand control is usually found more satisfactory, although care is required to avoid leaving the receiver at low gain after a local communication to ensure against the loss of a distant call. This problem does not arise in the case of civil aircraft, which can therefore take advantage of the automatic form of control.

(6) Weight

It would seem perhaps unnecessary to stress the necessity for reducing weight to a strict minimum where aircraft installations are concerned, but to those who have occasion to examine odd components which the originators or designers intend for use in aircraft it is evident that the point is not sufficiently appreciated. Every pound added to the installation in an aircraft causes indirectly the addition of another 3 lb. distributed between wing structure, engine, propeller, and fuel.† This proportion may appear fantastic, but if it only helps to focus attention on this aspect of design it will have served its purpose. Weight is not represented by the mere weight of the apparatus as usually produced by the designer; there are innumerable additions to it in the form of cabling, cleats, fittings forming permanent features of the aircraft structure, crates and suspensions, aerial posts, and, last but not least, ignition screening and also screening and suppressing of the other electrical equipment with which the aircraft is fitted. These features will be referred to in their appropriate Sections of the paper.

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* Of normal performance.

† In the case of an aircraft operating at the limit of its range, when useful load represents only one-hundredth part of its weight, every additional pound causes proportionately greater increase in total weight.

(7) Bulk

Bulk is not to be taken as a kind of alternative to weight; although intimately linked up with it, it is a subject which demands special attention. A view of the internal arrangements in the passenger compartment of a large modern aircraft gives one the impression of spaciousness as compared with the cockpit of a smaller aircraft, and particularly of a military aeroplane. But when one looks into the pilot's cockpit and other active compartments one is struck by the overcrowding which exists there. Compactness is therefore a consideration of prime importance, and more especially so in respect of components such as remote controls, switches, indicating instruments, and the like, which have to be located within reach of the pilot or wireless operator and on the instrument board.

But bulk and weight are not so easily kept down as might be supposed at first sight. When apparatus is designed for direct operation or observation it is necessary to locate all controls and even plugs and sockets on one face only of the instrument. This very frequently renders the internal arrangement of the components somewhat awkward, and designers are hard put to it to compromise evenly between the claims of weight, bulk, efficiency, and wiring convenience. An incidental consequence of reduced weight and bulk is the reduction in the dimensions and weight of the crates or means adopted to support the apparatus in the location chosen for it. This point will be further remarked upon in the next Section.

(8) Vibration

One of the most troublesome features of aircraft radio-communication is the insidious effects of vibration. Considering the power and speed of the engine, the aerodynamical reactions of the air-frame (which includes wings, fuselage, and tail), and the forces acting on the propeller, it is not surprising that vibration is at a rather high level.

Very careful attention must be given to the secure locking of all screws and bolts and the tying-down of all anchorages in the wiring. Methods of locking and securing which are normally found satisfactory for occasional mechanical shock and vibration are frequently unreliable when subjected to the continuous trepidations to which this class of apparatus is subjected in aircraft. It is generally found preferable, at some inconvenience, to secure internal screws and bolts by cementing them in place with a touch of varnish or like substance.

But the chief difficulties occasioned by vibration are in connection with the frequency stability of the radio-communication circuits and electrical stability of components. These vibration effects belong to two separate classes: (i) direct transmission, and (ii) air-borne vibrations. The former are fairly easily dealt with, but the latter have been more troublesome. These two classes will be considered together in the following paragraphs.

(a) Wiring.

In the earlier part of the period under review, when operation was limited to medium frequencies, the effects of vibration on the emitted frequency were not sufficiently marked to cause excessive difficulty in maintaining communication, and the original practice of employing self-oscillators directly coupled to the aerial subsisted for a prolonged period. The only attention which it received was in connection with stiffening and secure positioning of the wiring carrying high-frequency currents. This was done in order to prevent wires carrying currents at high potentials coming into contact with, or excessive proximity to, other wires or parts at different potentials. But from the earliest days extreme difficulty has been encountered in connection with reception, where the " microphonic " properties of the valve electrodes imposed severe limitations on the overall amplification which could usefully be employed.

(b) Microphonic valves.

Microphonic trouble with valves can be said to be contemporary with the introduction of the dull-emitter filament. Early valves of this class generated a continuous ringing sound in the telephones, which completely swamped weak and even medium signals. It was therefore usual to select valves having this characteristic present to a minimum extent, and these were reserved for use as detectors, where the trouble was most felt. Medium-quality valves were employed in the early stages of amplification, and bad ones in the output stage; valves of excessively bad quality were relegated for use in ground receivers.

This process of selection was, of course, unsatisfactory from the point of view of contract inspection, and the issue to valve manufacturers of valves of " standard " non-microphonic properties for use in comparative inspection by the " hit it and listen " method was soon found impracticable and unsatisfactory. Exhaustive tests were carried out to determine the causes of microphonicity, from which it was soon appreciated that the chief cause of the trouble was the resonant vibration of the filament. The grid and anode were sometimes also responsible for microphonic effects, but to a much smaller extent. For many months a special valve was reserved in Air Ministry laboratories for sensational demonstration, for it vibrated in four different ways: one mode and its harmonics for the filament; two modes for the grid, which responded as a whole and also owing to its coiled-spring construction; and one mode for the anode. All these responses were of a different order of frequency and all could be seen with the naked eye.

There followed a period of rapid and marked progress, manufacturers paying special attention to the anchoring of the filament and to its general stiffening. The response frequency was thereby raised and the damping increased until it was no longer a serious cause of trouble. Some ingenious constructions were proposed and experimented with, such as the resilient mounting of the complete valve in an evacuated envelope, but these forms were soon to be dropped when valves reached a high degree of non-microphony. The subsequent development of the multiple-suspension filament afforded a still more marked improvement, and it can now be said that microphony is a thing of the past. The growth of broadcast reception played no mean part in the elimination of this extremely annoying defect.

(c) Microphonic circuits and components.

But valve microphony is by no means the only cause of vibration-produced radio-frequency instability. The rather flimsy construction of the variable air-condensers originally available caused serious frequency-modulation effects which adversely affected superheterodyne reception. These effects naturally produced a chopping-up of the received signal, which was particularly distressing in the case of telephony. Condenser designs had to be overhauled to ensure substantial rigidity and stability of the rotor and stator.

Receiver inductances, being usually wound on solid formers, naturally gave no trouble, but rigidity of the general wiring has had to receive careful attention to obviate changes in circuit impedance.

(d) Aerial vibrations.

Although belonging to a different class, the instability introduced by changes in aerial constants is conveniently dealt with in connection with vibration.

As was mentioned earlier in the paper, little trouble was experienced at first when medium waves were in use and ether congestion not yet a serious problem. The introduction of short waves, however, resulted in the immediate appearance of excessive frequency wobble when C.W. communication was attempted. It should be remembered that in those days it was still usual to employ self-oscillators and direct aerial coupling. Besides the slow but relatively limited frequency variations occasioned by the slow swaying of the short trailing aerials first employed, there appeared the pronounced effect of the rapid vibrations of the wire constituting the fixed aerial and also of the internal aerial and earth connections. The cure for this was of course the substitution of master-oscillator circuits for the direct-drive type, but unfortunately designers in those days showed no great anxiety to add considerably to the dimensions, weights, and power consumption of their transmitters, to say nothing of the difficulties that could be expected to arise in connection with the wide frequency bands in use and the requirements of frequency-changing. The problem was side-tracked for a time by utilizing either radiotelephony or I.C.W. It was not until frequency channels had to be reduced to their narrowest practical limits and the use of C.W. insisted upon that the problem of the small master-oscillator transmitter was tackled, but its introduction completely eliminated the effects of aerial instability. It is to be observed, however, that much care was called for in the design of the master-oscillator circuit to guard against vibration effects. As an illustration of its effectiveness, the case can be quoted of a small battery-driven transmitter working on a wavelength of 30 metres which when deneutralized gave a frequency instability of the order of 30 000 cycles per sec., whereas when properly adjusted the instability was unobservable by ear, thus showing a value of less than 20 cycles per sec.

(9) Noise

Owing to its close association with vibration, noise may conveniently be considered as the next cause of difficulties.

Noise affects radio-communication efficiency in three ways: first, in connection with its direct effect on the valves, as already considered; secondly, in relation to the speech efficiency of the microphone when telephony is employed; and thirdly, in respect of aural reception.

(a) Microphones.

From the earliest days of radio-telephony the direct impact of extraneous sound waves on the microphone was a cause of considerable trouble. The subject was actively studied in many quarters, but perhaps nowhere with such insistence as in the R.A.F., where telephony occupied an important place. Starting from standard ground-type microphones held in the hand and completely unprotected from the effects of external noise and, incidentally, of wind and slip-stream, there were developed many types of protected hand-held microphones giving a gradually improving ratio of speech to noise. Many designs were evolved in England, and particularly in America, in which an attempt was made to balance out the unwanted noise while retaining a certain amount of sensitivity to the closely-applied vocal sounds. But, on the whole, improvements were slight and not infrequently quite negligible.

Seeing that there was little hope of keeping noise out of the microphone even when the latter was completely enclosed in a padded mask, which incidentally introduced serious acoustical difficulties, the problem was attacked from the point of view of the sonic spectrum essential to intelligible speech. It was soon realized that it was desirable to eliminate response to frequencies below 700 cycles per sec. or thereabouts—this, more by good luck than good design, was already partially catered for in the characteristics of the microphone soundbox, of the speech transformers, and of the earphones. It was also ascertained by trial and error that frequencies higher than about 2 500 cycles per sec. were unessential to the production of satisfactory speech in the presence of aircraft noise. Further progress was made on this basis, but such progress was always behind requirements, owing to the fact that aircraft engines constantly increased in power and air speeds rose.

The introduction of the combined oxygen and microphone mask was another serious setback, the requirements of the one clashing with the needs of the other. The necessity for ventilation reintroduced extraneous noise and wind effects. A further complication arose when it was required to use the microphone while lying prone on the floor. Nevertheless, there was produced a useful compromise in the form of a microphone fitted to a ventilated oxygen-fitted mask and capable of being used in all positions except with the operator lying on one side. This microphone is shown in Fig. 9. The chief point of interest is the fact that the capsule is held with its plane normal to the face of the user and is double-sided.

As the level of aircraft noise showed unmistakable signs of increasing still further, it became necessary to study the problem from a more scientific point of view. It was soon realized that no amount of filtering in the electrical circuits could produce any appreciable improvement, for the main trouble was caused by the non-linearity of the carbon microphones then in use. Acoustic filtering appeared to be out of the question, although of recent years much has been done in telephone laboratories to modify the characteristics of the diaphragm and impart to it a filter action cutting off the lower frequencies. It thus became apparent that the only hope of appreciable relief was to be found in the use of microphones possessing substantially linear characteristics. It is too early to state with certainty that by this means adequate quality may be hoped for, but results of tests on linear microphones are promising. Various types have been produced, such as the crystal class and the electromagnetic type. Unfortunately all these types are considerably less sensitive than the carbon type, even when the latter is relatively insensitive for use in noisy surroundings. The loss of sensitivity can be roughly expressed as 20 db., and can only be compensated by the provision of a pre-amplifier. This, unpleasant as it may appear at present, will probably have to be accepted if telephony is to survive. With linear microphones the noise of that part of the spectrum which for obvious reasons cannot be eliminated, is heard as an independent background but does not cause the distressing " chopping up " which is the consequence of inter-modulation.

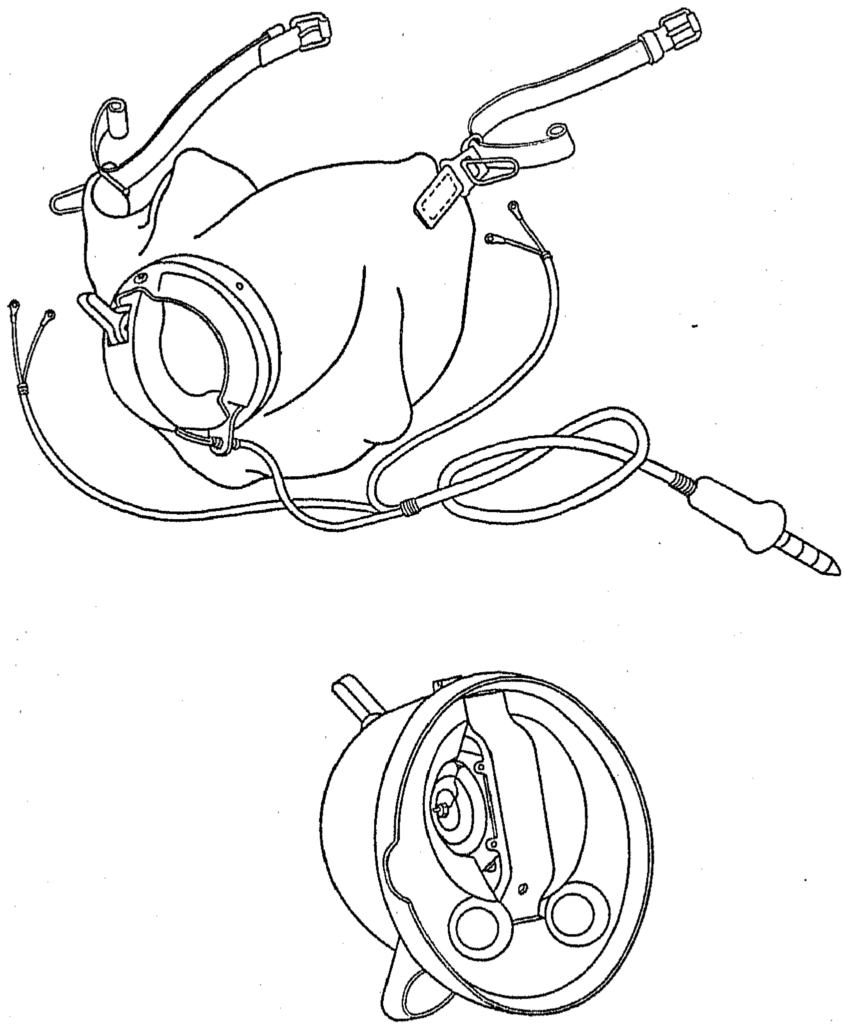

Fig. 9.—Mask microphone.

It is desirable to refer here to a class of microphones which is frequently brought forward as the obvious cure for noise background; it is the type in which the microphone capsule is applied externally to the larynx, and sometimes to the face at the corner of the mouth and other places, with the object of leaving the mouth free while sealing off the capsule and the diaphragm from the extraneous noise. Over a period of 20 years, ever since the War in fact, this class of instrument has been repeatedly tried and experimented with under all possible conditions, but with complete failure. It is not meant to imply that this class of microphone is incapable of providing satisfactory service; in fact, it is known to be sufficiently satisfactory for use with good results in noisy surroundings such as power stations and industrial shops. But aircraft conditions are too severe for it, and if it is designed to eliminate noise its acoustic characteristics are such as to produce speech of low intelligibility. Its application to aircraft for continuous use over a period of an hour or more is further debarred on account of objections of a medical nature. In military aircraft, where high altitudes and the use of oxygen is almost a normal state, the pressure on the jugular vein is a source of danger, and it is not easy to produce a design which shall be comfortable, safe, and efficient. Perhaps a more intensive study would overcome the above difficulties, but the outlook is far from promising.

(b) Telephones.

The other effect of noise is its direct action on the hearing of the operator. Noise is " heard " not only through the normal agency of the outer ear but also more directly through the cranial bones. From the earliest days, noise has been kept in check by wearing a helmet in which the telephone receivers were inserted. The relief afforded by this practice is considerable, but the gradual increase in noise level has made it more and more imperative to ensure an excellent fit and to provide substantial padding. This latter feature, however, has made the problem of ventilation of the outer ear increasingly difficult. The design of the helmet itself has had to receive special consideration in order that eddies round the receiver-pad might be reduced to a minimum. As a matter of quantitative interest it may be mentioned that noise level at the operator's or pilot's unprotected ears has already grown to the value of 135 phons, which is the threshold of physical or, shall we call it, mechanical sensation. This energy level is about 1 million times that observed in the carriage of an express train.

The proximity of the pilot to the magnetic compass caused considerable trouble in the form of magnetic deviations occasioned by the presence of the small but relatively strong magnets in the earpieces. Deviations of the order of 20° with the headphones at a distance of 18 in. were quite usual. Advantage was therefore taken by the Air Ministry of a proposed redesign of this component to provide a soft-iron case in lieu of the usual brass one; by this means the deviation was reduced to about 1° at a distance of 6 in.

The type of telephone receiver used in the R.A.F. being rather special, it may be of interest to mention its principal features and the reasons for their provision.

In the first place, as has just been noted, the containing case is of soft iron to eliminate stray fields. Secondly, the metal case is completely enclosed in an insulated covering which is moulded in position; this ensures that in the event of the internal windings being accidentally connected to the 1 200-volt circuit this potential shall not be applied to the operator's head. For the same reason there is fitted between the iron diaphragm and the outer cap a disc of mica which prevents conduction by moisture, which is invariably present on the surface of the earcap after it has been worn for a short period.

(c) Magneto noise.

There is another class of " noise " which is not of acoustic origin, namely " magneto noise " and general electrical disturbances.

Magneto noise was first encountered during the War, when multiple-stage valve amplifiers were first employed. It appears as a steady purring sound of great intensity and penetrating power. It is caused by the production of highly damped high-frequency currents, generated principally in the H.T. ignition leads to the sparking plugs, but also to a quite important extent by the spark at the contact-breaker (which causes disturbance in the L.T. and magneto switch wiring) and by the spark at the distributor.

After some unsuccessful attempts at devising high-frequency chokes to be introduced in the receiver aerial connection, recourse had to be had to complete screening of the H.T. leads, and this was later followed by screening of the complete magneto system. The continued increase of receiver-gain and the tendency of radio towards shorter waves rendered this treatment of the magneto quite inadequate. A second step was taken when the braided screen was bonded to earth by the shortest possible path every 6 in. or so of its length. Finally, there has been added a complete metal screen round the sparking plug. This has resulted in practically complete elimination of magneto noise. To illustrate the point it may be stated that with a perfectly screened system of this kind it is possible to detect the presence of a town 2 000 ft. below the aircraft. Magneto noise is not generally sufficient to make it necessary to provide 100 per cent screening when the operating wavelength is of the order of 1 000 metres or more. As the frequency is increased, so screening must be improved, until it is found necessary to provide the final refinements for aircraft on which very short waves are received.

The above remarks apply equally well to coil ignition, which, with a few appropriate modifications, is treated in the same fashion. This type of ignition necessitates that the supply battery be completely screened or fitted with suppressors at the magneto end.

(d) Electrical interference.

Perhaps the first appearance of electrical interference in aircraft was due to the vibrating-contact regulator which at one time was employed to maintain the generator voltage at a constant value. After some attempts to find a palliative in the insertion of chokes and condensers, this class of regulator was discarded.

In order not to labour a point which is now of universal experience in connection with ground installations, this class of interference will be dismissed with a mere reference to all the types of rotating or contacting electrical machinery to be found on aircraft. These are: general service generators, motor-generators for the radio-communication equipment, servo motors for the aircraft controls, relay circuits, etc. All these cases are dealt with by the normal method of inserting filters at each source of interference.

(10) Temperature

The effects of changes of temperature on the performance of radio apparatus for aircraft were not felt until the need for a high order of frequency stability had arisen. In recent years this has become an acute problem in view of the steady and general narrowing-down of radio-communication channels and the increased height at which aeroplanes are flown. Apparatus which is of a sufficiently high order of frequency constancy for use on the ground is often affected to a serious extent by the temperature variations met with during flight. Roughly speaking, it can be said that this temperature variation frequently reaches a value of 60 deg. C., i.e. from + 20° C. on the ground to − 40° C. at an altitude of 30 000 ft. In the case of closed-cockpit aircraft the range of temperature is usually 10 to 20 deg. C. less. This large range of temperatures may be covered in the course of half an hour, allowing for the partial protection of apparatus by the surrounding fuselage. With the early designs of inductances and condensers it was not at all exceptional to meet with temperature coefficients of 150 parts in 10^6 per deg. C., which, at a wavelength of 50 metres, represents a change of 1 000 cycles per deg. C. or a possible total variation during one flight of 60 kc./sec. Before the close packing of channels it was necessary for the receiving operator to search more or less continuously over a frequency band of the above order, and although reliability of communications suffered there did not result any serious interference with other users of neighbouring frequencies.

With tightened restrictions and the use of master oscillators, it became essential to reduce these effects to the lowest possible value. A detailed examination of components showed that the greater part of the variation was due to the designs of the inductances, especially of the self-supporting tubular type used in transmitters, but in many cases fixed condensers also played an important part. By careful selection of commercial condensers of the tightly clamped type the part played by this component was considerably reduced, and coefficients of the order of 20 parts in 10^6 were fairly regularly obtained. Things were not so favourable in respect of the fixed type of condenser designed to carry relatively large high-frequency currents and to sustain high high-frequency potentials. These continued to give serious trouble until designers had to be reconciled to the provision of condensers of increased size and heavily clamped.

A very marked improvement in inductance coils was obtained by the use of copper tubing shrunk on to heavy supports built up of one single material. In some designs the helical tube was forced open on the inside of the support. These constructions reduced the temperature coefficient to the order of 40 parts in 10^6, and overall stability of 60 parts in 10^6 was obtained. But this residual instability remained a source of difficulty, in the case of transmitters, implying as it does a possible frequency-change of 10 kc./sec. in the most favourable cases, with quite frequent excursions up to 20 kc./sec. This drift caused annoyance to neighbouring channels and was of course detrimental to good reception on the ground. Many attempts were made to produce a form of inductance having sensibly zero temperature-coefficient, with the intention of removing not only long-period variations but also the variations due to heating of the master-oscillator coils by the high-frequency currents circulating in them. The rapid frequency-drift caused by ohmic losses is a particularly important question in connection with aircraft radio, where the master oscillator cannot be left permanently switched on during reception. Of the various forms tried, two may be mentioned which, although never brought into regular use, showed a certain measure of success. The first one consisted in building up the helix of individual rings joined end to end by means of a flexible strip and maintained in a state of compression by an outer supporting frame. A more satisfactory scheme involved the use of suitably constructed bimetallic strips of silver and copper. With certain proportions of the two metals it is possible to arrange that expansion of individual rings as a whole is compensated by the curling-up caused by the difference of coefficient of thermal expansion of the two elements. By this means a very constant inductance could be obtained. It was marred, however, by mechanical defects which tended to produce sudden, though small, changes with sudden relief of stress. A typical coil of this description is shown in Fig. 10. It will be obvious that with suitable proportions for the two metals the individual rings can be made to contract and so compensate in a large measure for the changes in the remaining components in circuit. A typical case may be quoted in which the frequency-change at 10 Mc./sec. was of the order of 200 cycles per sec., compared with 6 000 cycles per sec. in the case of a normal rigid coil.

The obvious cure for temperature effects is of course the use of crystal oscillators, and these were extensively used in America and are gradually growing in importance. Unfortunately the use of crystals ties the service down to a pre-set frequency, with the consequent possibility of jammed communications. In this connection one may recall the breakdown of communications in certain foreign naval exercises, due to interference from transmissions by another foreign power. The important advantages conferred by the use of crystal-controlled oscillators have forced designers to incorporate in their designs a number of alternative crystals in order that rapid and accurate frequency-changes might be obtained. With the introduction of zero-coefficient crystals this form of oscillator is being rapidly brought into use both in transmitters and in superheterodyne receivers. In the author's opinion, however, crystals should not be used as an excuse for bad coils and circuits. Should it be necessary at any time to revert to uncontrolled master-oscillators, the frequency must at least be of such stability as to produce a carrier wave free of frequency modulation under conditions of vibration.

Another effect of lowered temperature is the serious falling-off of accumulator performance at temperatures below − 30° C. At these low temperatures it is not always possible to draw the normal current demanded by the equipment, and invariably the ampere-hour capacity is seriously reduced. This effect has not, as far as the author is aware, caused sufficient curtailment of performance to warrant the taking of special measures to keep the accumulator warm, but it is a point that may require attention in the case of aircraft flying regularly at high altitudes for long periods.

The relatively recent introduction of electrolytic condensers in aircraft apparatus, principally in smoothing circuits, has revealed the weakness of this class of component from the point of view of temperature. When the temperature is sufficiently lowered, chemical action practically ceases, and the condensers fail to perform their normal functions. This is a serious blow to the designer, who is thus prevented from using a component which is particularly valuable from the point of view of bulk, weight, and efficiency, unless he is prepared to provide artificial heating for the complete apparatus or at least for these sensitive components.

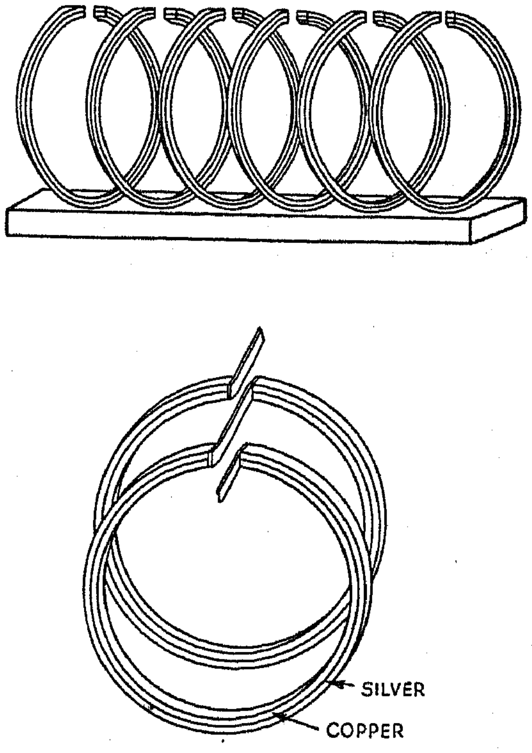

Fig. 10.—Bimetal coil.

(11) Atmospheric Pressure

It may be opportune to mention at this stage the very serious effects of lowered atmospheric pressure on the performance of the equipment.

Exhaustive tests have shown that the insulation of transmitter circuits is seriously reduced by corona losses over the surface of insulators and at sharp points. The effect is sufficiently serious to necessitate increased leakage paths and the use of air insulation and avoidance of sharp points in components at high potentials. Transmitters which appeared to be adequately insulated for use at 20 000 ft. were found to break down at 25 000 ft. and above.

A further effect of lowered atmospheric pressure relates to the efficiency of radio-telephony. This is affected in two ways: one is the reduced vocal output of the speaker due to partial exhaustion as well as to the reduced weight of air displaced by the lungs; the other is the lowered efficiency of the carbon-type microphone, which tends to " pack " and has its pressure/resistance characteristic impaired. Whereas there is no practical cure for the former, the latter can be eliminated by the use of non-carbon microphones and pre-amplifiers.

(12) Voltage Stability

Reference has already been made, in the Section dealing with " Power Supply," to the question of voltage regulation. The necessity for constancy of supply voltage both for H.T. and for filament heating is not peculiar to aircraft radio, but the difficulty in ensuring it is more apparent in this class of installation owing to the lightness and small overload factors of the equipment. Initially it was the practice to employ accumulators for filament supply, and, considering the frequency tolerance that was then accepted by all, no trouble arose. But accumulators in aircraft are a source of inconvenience and danger. It is not possible to ensure that the containers shall be absolutely dry externally, and, in particular, free from acid. In consequence, electrical leakages to the crate are not unknown. Besides the risk of fire there is danger of damage to the wooden structure, which may become acid-soaked and finally destroyed.

To avoid this difficulty and at the same time to reduce maintenance, dual-purpose generators were designed in which a high standard of regulation was required. It was usual to call for 5 per cent regulation both for the high-voltage windings and for the 12-volt supply. (It will be conceded that for a generator delivering 120 watts at high voltage and 48 watts at low voltage this figure is low.) Furthermore, it was considered essential to render the two outputs independent of each other, thus necessitating two armatures and two fields. This requirement further intensified the demand for constant speed at all loads, in order that sudden application of the H.T. load should produce no change in the L.T. voltage. Manufacturers have been able to produce generators satisfying completely these rather severe requirements. In this connection it should be noted that dynamotors and single-field machines fall far short of requirements.

For many years this class of machine gave satisfaction when used in connection with medium-wave transmitters. With increasing use of short waves, however, and particularly for unmodulated telegraphy, the H.T. stability quoted above was insufficient to produce signals free from keying-chirp—the change of frequency which occurs immediately after pressing the key. This effect was intensified by the tank condensers and filter circuits which were habitually connected in the H.T. mains to absorb generator ripple.

Investigations showed that considerable improvement could be obtained by inserting in series with the anode feed a resistance equal to the circuit impedance, namely, the ratio of supply voltage to anode current, which, with the valves and circuits generally in use at that time, was about 30 000 ohms. This figure, however, was too large to be acceptable, as it involved heavy losses and overall inefficiency. It was also dependent on the transmitter adjustments, and so a compromise figure was adopted and a 10 000-ohm resistor was provided. The results were satisfactory, although somewhat imperfect. As motor-generators or dynamotors began to take the place of wind-driven machines the dual-purpose requirement had to be dropped, and accumulators were reintroduced for filament heating.

It is convenient to refer here to the need for a low proportion of generator ripple. Generator ripple is occasioned both by slot conditions and by commutator design. Early generators were particularly bad from this point of view. When they were used on telephony the background of noise was so great as to necessitate the application of smoothing circuits capable of reducing a 20 per cent ripple to a value of 2 per cent. This very undesirable item of equipment was a great incentive to designing a ripple-less generator. Utilizing the design of slots and commutators studied by the Air Ministry, the electrical trade has been able to produce generators which show a peak ripple value on full load not exceeding 1 per cent on the high-voltage winding. This proportion of ripple was acceptable for transmitters, but in view of the fact that the generator was frequently kept running during reception, albeit its fields were open-circuited, the background of interference on the receiver was considerable. Although smoothing chokes could be dispensed with it was necessary to retain the tank condenser, which was connected as near to the generator as possible.

(13) Intercommunication

In order to allow the occupants of the aircraft to exchange verbal messages, provision was originally made for speaking tubes. These are still in frequent use and are often preferred to more modern equipment. This is not entirely a question of conservatism, for very frequently electrical methods have proved unsatisfactory. It is not proposed to go into the pros and cons of the two systems, but it is necessary to refer to electrical intercommunication on account of its relation to radio reception and radio-telephony. No particular reference will be made to plain electrical intercommunication, since this is not a radio problem, but stress will be laid on intercommunication linked up with the radio-telephone equipment and with the radio receiver.

Before the introduction of mask-microphones whose special feature is to allow the occupants, and particularly the pilot, to have free use of their hands, it was usual to fit a hand-held microphone near at hand and to wear headphones fitted in the helmet. These were connected to a battery and transformer. In those days noise level was sufficiently low to allow of audible speech being produced without the need for amplification. With the increase in noise level, especially in open-cockpit military aircraft, it became necessary to add a single-stage amplifier. This was of sufficient output to produce a mean telephone input of 10–15 volts and was moderately efficient, but under present conditions an output of the order of 30 volts is usually needed. In order to reduce noise level it was usual to provide press-to-speak buttons in each microphone circuit so that the background of noise in the headphones could be limited to that due to one microphone only instead of two.

In the case of multi-seater aircraft and of military machines in particular it is necessary to allow conversations to take place while the wireless operator is engaged in reception. This entails the provision of selector switches under the control of the pilot and of the wireless operator whereby the former may be enabled to speak with any member of the crew or all of them at once, while the operator may cut himself off should he be receiving an important message under conditions of weak signal strength.

Complications arise in the case of the aircraft fitted for telephony working, as it is then necessary to leave full flexibility of conversation within the aircraft while ensuring that such conversations are not accidentally radiated should it be necessary for one of the crew to make use of the air-to-ground or air-to-air telephone link. This is merely a matter of appropriate interconnected switching, but it is mentioned in order to show that even the simplest services are a source of operational difficulty where an aircraft is concerned.

With very noisy aircraft the telephone voltage and power consumption reach such a level as to necessitate a higher degree of amplification. In order to avoid further increase in weight it has been the practice in recent years, particularly in two-seater military aircraft, to make use of the output stage or stages of the radio receiver. There has been provided, therefore, switching means to enable the microphone circuit to be disconnected from the radio transmitter and joined to the low-frequency stage of the radio receiver. This method is particularly convenient and efficient in two-seaters, but is of course inadmissible in multi-seaters where the radio receiver must be available at all times without interference from internal conversations.

In some cases it is necessary to provide intercommunication between the speaking-tube and the telephone systems. A satisfactory solution has been found in the provision of an adaptor between the telephone and the helmet clip. This adaptor is provided with a through passage for the sounds emanating from the telephone receiver and is fitted with a branch tube for connection to the speaking-tube system.

Many attempts were made to provide sound-screening for the microphone before the introduction of the mask type, but none proved satisfactory. As an illustration may be quoted the provision of a speaking tube conveying speech to a totally enclosed and sound-proofed microphone. The chief difficulty encountered was the bad acoustic quality of the tube and terminating chambers, and it did not appear profitable to attempt to design an acoustically-matched system.

Present practice utilizes either the receiver output or the independent amplifier. In noisy aircraft an output of the order of 20–30 volts, i.e. 25–30 milliwatts per receiving point, is necessary. It will therefore be appreciated that telephone-receiver design of the commercial type is quite unsuitable for such heavy outputs, the ordinary diaphragm being apt to rattle and render speech unintelligible.

(14) Listening-through

At quite an early period in the development of radio it was not unusual to arrange for control of the transmitter and receiver by the telegraph key. This enabled the listening operator to interrupt the transmitting operator by causing signals to be heard in the intervals between dots and dashes. This practice died out with the advent of valve-operated transmitters and valve receivers used under aircraft conditions, owing to the interference caused by the continuously-running generator. But as listening-through became a vital military requirement attention had to be paid to the design of devices which would permit of this operation.

Considerable attention was paid in the R.A.F. to this kind of device, and many alternative forms of electro-mechanical listening-through keys were tried before a satisfactory one was evolved. The requirement was that the transmitter and receiver were to be alternately switched over to the aerial at morse speed. Safety of the operator and of the equipment demanded that the following operations be performed in the order given: (*a*) Change over from " receive " to " send." (*b*) Make H.T. + connection to transmitter. (*c*) Make transmitter key circuit.

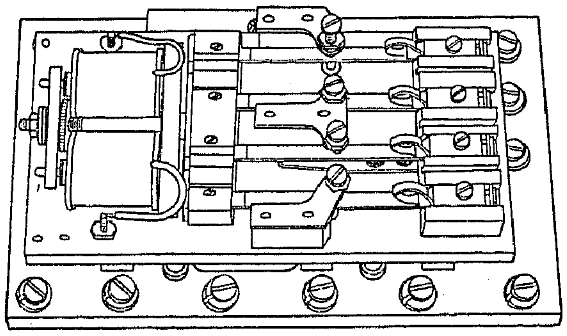

Fig. 11.—Key listening-through (T.21 and T.19).

It was important to ensure precision in the order given in order to avoid any possibility of high voltage reaching the receiver and so endangering the comfort and perhaps the life of the operator. For use in emergency a dummy listening-through key was provided which, on being plugged-in in the place of the real one, effected normal connections through the hand-operated send-receive switch. Various designs were produced, of which that shown in Fig. 11 is a typical example. This particular form was its own dummy when reversed back to front. With this mode of working it was unavoidable that a certain amount of key-click interference should reach the operator's headphones, but with substantial H.T. filtering excessive generator noise during receiving periods was obviated.

In recent years an improved form of listening-through has been introduced having the advantage of simplicity and safety, together with the elimination of a special instrument. It consists in coupling the receiver directly to the aerial (which is common to the transmitter) through a very small series capacitance of high insulation. With the transmitter permanently connected to the aerial, its tuned output circuit affords an extra resonant circuit for the receiver, thus increasing the selectivity. It has the further great advantage that the aircraft transmitter can be automatically set to the ground-transmitter frequency as the operator tunes in the signal from the latter. This ensures accurate setting-up on the wanted frequency without necessitating the use in the aircraft of an accurate wavemeter. Naturally this method does not permit of working on different frequencies for transmission and reception, but as the same frequency is normally intended to be used in each direction this limitation is not at all an undesirable one. Nevertheless, it is possible to revert to complete flexibility by operating the send-receive switch when the two frequencies need no longer be identical. The value of the coupling condenser is so chosen as to limit the interaction between the transmitter and receiver tuning circuits to a negligible minimum, and it further ensures a reasonably low voltage across the receiver coils during transmission. Nevertheless, it was found that the induced voltage across the grid-filament circuit of the first valve was sufficiently high to impair the emission of the filament in a relatively short time and also to cause insulation troubles in the valve itself. To overcome this defect a diode is connected across the tuned circuit with a negative bias of about 0·5 volt on the anode; this removes the valve load from the tuned circuit during reception but introduces heavy damping in the receiver during transmission. A special high-emission valve, free from anode current at very small negative anode potentials, was designed by the manufacturers and satisfactorily fulfils requirements.

Although this form of reception has been in regular use in the fighting services for many years, it has not yet been applied to civil aviation, but from recent inquiries it would appear that designers of civil-aviation radio apparatus have the matter under consideration.

The necessity for a high degree of generator-noise suppression in connection with L/T. operation necessitated the carrying of heavy and bulky H.T. filters, and with high-gain receivers even the noise of the generator for the transmitter filaments was troublesome. Attention was therefore turned to the study of generator windings and commutators, with the result that generators are now available in which the mean H.T. ripple on load is of the order of 0·3 per cent without additional smoothing, while the L.T. ripple is of the order of 0·75 per cent on full load. A pair of small condensers of 10 milli-microfarad capacitance are connected across the brushes and to the carcase of the machine to remove oscillatory interference caused by commutator sparking.

It is evidently so desirable to relieve the operator, who may be the pilot of a fighter aircraft, of all unnecessary operations that voice-operated switching of the type regularly applied to ground systems would appear to be worth developing. Such a system must have the following characteristics: (i) It must change over from "receive" to "send" immediately speech is applied to the microphone. (ii) It must be entirely unaffected by external noise. (iii) It must not respond to change of external noise-level. (iv) It must be unaffected by change of altitude. (v) It must be unaffected by change of temperature.

To these requirements should be added the remark that there should be no tendency to remain in the transmitting condition when speech is not being applied to the microphone. Such an occurrence would destroy communications in the whole of the squadron.

Exhaustive trials made by the Air Ministry showed that the valuable feature of automatic and instantaneous change-over was offset by lack of reliability due to any or all of the following causes: (A) The difficulty of applying a background suppression when the background is subject to sudden change, such as when the pilot turns his head and when engine speed is altered or when guns are fired. (B) The failure of electrolytic condensers at low temperatures. (C) The reduction of speech level at high altitudes.

A solution may perhaps be forthcoming in the future, but at present the conditions would appear to be very unpromising.

(15) Accessibility and Remote Control

These two aspects of aircraft radio are intimately related, and are perhaps best considered together.

In early aircraft installations it was the practice to locate the whole of the equipment within reach of the operator, and although weight was an important consideration the stress placed on small bulk was less insistent than obtains at the present day. With the introduction of pilot-operated telephony apparatus it became essential to install the whole of the equipment in an inaccessible position and to provide remote control for the send-receive switch, the receiver tuning, and the volume control. Although flexible Bowden-cable controls were in general use in civil installations and were easy to install by virtue of their high degree of flexibility, they were found unsuitable for use in connection with the superheterodyne receivers which were in use in the R.A.F. The chief defect was their excessive backlash. A more rigid system was therefore designed, and although it had the disadvantage of greater weight and was more difficult to install it withstood the test of time and gave satisfaction from the point of view of operation. It consisted of a multi-layer short-lay cable encased in a solid tube, bent into shape as was demanded by the run of the controls and the layout of the apparatus. Controls of this description are now commercially obtainable and are used for all kinds of purposes. It would be outside the scope of this paper to describe the alternative types in detail.

In recent years there have been developed in various countries types of remote controls employing electromagnetic relays. These have the great advantage of simplicity of fitting and wiring, against which must be offset the extra load demanded from the battery supply. In general, electromagnetic systems are very satisfactory for actuating switches and the like, but as far as the author's experience goes no existing design is completely satisfactory in respect of receiver tuning control, where very fine and continuous adjustments are required. Although various forms of commercially-available electrical tele-controls have been tried, none has yet been found which fulfils rigorously the demand for precision required for tuning controls. They are ideal, however, when used in connection with multiple spot-wave apparatus, especially when this is of the crystal-controlled type.

The relegation of the bulk of the apparatus to the rear bays of the fuselage has raised the important question of accessibility, quick installation, and easy inspection. Modern practice is to mount the whole of the equipment in a metal framework or crate, adequately fitted with elastic suspensions and shock absorbers, and to slide the complete crate through a removable panel provided in the side of the fuselage. The evolution of the crate has been slow but steady. It originated in the crude brackets which in the early days were secured to the structure of the aircraft. These brackets and the type of elastic suspension used varied in different countries and as between civil and military aircraft. They were required to absorb vibration and shock and yet to remain sufficiently rigid for ease of adjustment, and to be readily detachable. Whereas foreign practice rather favoured helical springs as shock absorbers, the practice in England was to use heavy braided rubber cord, which was found preferable from the point of view of damping of oscillations after a bump. With the introduction of crates carrying the whole of the equipment, including the power unit and batteries, the use of elastic cord had to be discontinued. It has been replaced by sponge-rubber slabs and by balls of the same material. This technique has been found particularly effective in the case of catapulted aircraft. Another widely-used form of shock absorber is the rubber-disc type, in which a central member is secured to the apparatus while an external fitting clamps the disc to the structure or carrier. There are many other designs, which it would be tedious and unprofitable to describe. Sufficient has been said perhaps to indicate the nature of the problem and the most promising lines of attack.

(16) Fire Risk

In aircraft more than anywhere else the risk of fire is a cause of constant worry to the designer of apparatus and of its system of installation. The complexity of the installation in such a small space and the minimum safety factors that are forced upon the designer make it necessary to look upon every component and device with suspicion. The risk of fire must be considered not only when the apparatus is functioning normally but also when faults occur.

Fire may be occasioned by overheating of cables and connections or by accidental damage caused by the breakdown of some component. The obvious thing to see to is adequate insulation and protection of terminals and plugs and sockets, and heavy covering of high-voltage cables. The aerial circuit in particular requires careful attention so that moisture deposited on insulators may not give rise to tracking and possible ignition of woodwork. But perhaps the most fruitful source of trouble is the battery circuit. Fires are frequently started by surface leakage over the accumulator case, along the wooden crate in which it is held, and back to a terminal at the opposite end of the battery. Much has been done towards the elimination of this danger by the provision of unspillable and splashproof accumulators, but to make doubly sure it is frequently the practice to fit insulating separators between the battery and the containing crate.

A peculiar type of fault encountered at one time took the form of serious overheating of the lead straps joining together individual cells. Examination having failed to bring to light any abnormal discharge or charging current which might account for the flameless combustion of the material round the battery lugs, the latter were sliced longitudinally, when it was found that the joint between the brass terminal and the leaden lug was frequently extremely poor; the resistance at this point was sufficient to cause the overheating observed. The manufacturers were apprised of the matter and immediately took the necessary steps to prevent its recurrence. One-piece terminals and plate lugs have afforded a positive cure.

A further source of danger occurs in aircraft installations should the aerial winch be allowed to retain any wire on the reel when the aerial is trailing for transmission. In early designs the aerial wire, which sometimes was allowed to remain on the reel, was a source of a heavy brush discharge and leakage through flaws in the ebonite or other material used. For the safety of the operator from the point of view of shock it is necessary to bond the complete winch to earth, and fire-risk considerations have made it necessary to terminate the aerial wire by a length of insulating cord and to reel out the wire right down to the plunger block which affords a connection to the apparatus. On more modern reels the insulation is adequate to allow the apparatus to be operated without removing the wire completely from the reel.

There is another class of risk which may conveniently be dealt with here. It applies equally to civil and to military aircraft and is connected with the installation of the battery supply and of the general electrical equipment of the aircraft. For reasons which will be given in Part I, Section (17), it has been the practice from the earliest days of the R.A.F. to connect the filament battery directly to the earth of the aircraft. This circumstance made it essential to utilize a separate battery for the radio equipment. There were other reasons for this practice, but this particular one remains when all others cease to be essential and vital. It will be appreciated that with one pole permanently bonded to earth the danger of the other pole becoming accidentally earthed is more serious than if both poles are normally insulated. A short-circuit on the unprotected battery means an end to all electrical services, some of which may be vital. But one of the greatest and more direct dangers is the possibility of igniting landing-flares in closed spaces, such as in hangars on land and on board aircraft-carriers. A further danger, which concerns others than the fighting service concerned, is the liability of releasing bombs by fusing of the thermally-operated cartridge-release mechanism. For this reason the radio accumulator has always been kept separate in the R.A.F., except when it is an indirect service such as the supply of power to a motor-generator. It is desired to stress the point that this condition is not peculiar to the fighting services. Fires have been known to occur in civil aircraft as the result of a fault occurring on the non-earthed pole of the battery. There is so little to be gained by earthing one pole of the general supply battery, through the use of a common earth-return in certain fittings, that it is a matter for surprise that this practice is still far from being an exceptional one.

It may be useful to draw attention to a form of risk which, while calling for no action on the part of the radio engineer, is attributable to him though it cannot result in a charge of carelessness being directed against him. I refer to the danger of causing induction of dangerous currents in the fusing circuits of bomb-release and flare-release mechanisms. When short-wave transmitters are operated in aircraft they are liable to induce currents in resonant circuits which may be of sufficient magnitude to operate fuse-released mechanisms. Experiments have proved that even with the low powers used in aircraft it is possible by being particularly careless in the run of the electrical wiring to induce currents of the required order of magnitude. The necessary conditions for resonance are obtained when the length of the wiring is about 1 quarter-wavelength or 1 half-wavelength, according to the position of the fuse in the circuit. Fusing may be caused by high-frequency currents at mid-points or by brush discharge at the ends. Complete screening is the only certain way of avoiding these dangerous resonances. But complete screening of the wiring, battery, and release mechanism is impracticable, and with partial screening there remains a source of considerable danger when aircraft are standing in the neighbourhood of powerful transmitters—in aircraft-carriers, for instance. Early designs of electrically-operated bomb-release mechanisms employed fused cartridges, and in view of the danger which has been mentioned it has been necessary to introduce relay-operated mechanisms, which are unaffected by thermal or brush effects.

As regards possible overloads resulting from faulty transmitter adjustments, regulations were made at one time whereby the standing anode current under non-oscillating conditions had to be limited to a safe value. This regulation made it impossible to employ high-performance valves, but the disability has recently been removed with the introduction of the pentode output valve, which can be adjusted to pass safe currents even when the circuits are completely out of adjustment.

It may be mentioned in passing that reliable fuses of the required current-carrying capacity are not readily obtainable, and when obtainable are liable to blow on slight but not dangerous overloads.

(17) Electric Shock

In an aircraft installation, involving the presence of H.T. voltages of the order of 1 200 volts in close proximity to the appliances used by the operator, substantial insulation of ground standards is ruled out, and great care is therefore necessary in planning the design and particularly the layout of circuits. The very small factors of safety which have to be accepted in the design of H.T. switches and components necessitate the use of circuits which in case of breakdown are incapable of directing high potentials into the components handled by the operator, namely the telephones, microphone, key, and aerial winch. This requirement is met by keeping the microphone, key, and telephones all at the same potential by connecting them to the filament battery and to earth. This ensures that no appreciable potential-difference can occur between these parts and the structure of the aircraft. Danger from the aerial winch is eliminated by the insertion within the transmitter of a blocking condenser of high insulation in series with the aerial terminal. There only remains, in the latter case, danger of unpleasant burns should the operator touch the aerial circuit with the power on and the key depressed.

To show the seriousness of the shock danger the case may be quoted of a fatal accident which occurred through the unhappy coincidence of a number of faults all essential to establish dangerous conditions. Firstly, the operator was wearing an ordinary metal-strapped telephone receiver; secondly, the generator was wrongly connected, thus cutting out the field regulator; thirdly, the windmill used on the generator was of too fine a pitch; fourthly, the ordinary electric battery supply was used instead of a special and separate one for the filaments; fifthly, the operator's boots were wet. During the flight the operator observed that his generator volts were excessive, the value being probably about 2 000 volts, and that the regulator had no effect upon it. He apparently went down on his knees to examine the generator (which was of the retractable type). The heavy overload he had previously applied to the set had caused an arc across the key and a breakdown in the send-receive switch between H.T. positive and receiver H.T. This had applied 2 000 volts to his telephones, the circuit being completed through his body to a bolt in the floor by way of his wet boot.

In modern installations this possibility is eliminated by the provision of highly insulated telephones, completely enclosed telegraph keys, and insulated microphones. In addition, safer circuits are employed. Any breakdown of the H.T. positive occasions a short-circuit of the H.T. generator, which may burn-out but will not occasion danger to the operator.

There is another form of shock which, while constituting no danger, can be particularly unpleasant; this is caused by high-frequency potentials of low value which are led into the microphone. When the mouth-piece is damp the operator perceives a slight burning sensation, which is decidedly more than a tingle and is particularly unpleasant. As it is impossible to ensure that all earthy components are at exactly the same potential, the occurrence of this effect is normally prevented by the insertion of high-frequency chokes in the microphone leads. In particularly difficult installations on aircraft built partly of wood and partly of metal it is frequently necessary to insert chokes in all leads from the transmitter to the external accessories. When the transmitter is intended to cover the short-wave band as well as the medium, the choke system may become very complex and a source of troublesome resonances. In this respect the modern all-metal construction has practically eliminated the problem of external lead resonances.

Reference has already been made to the insertion of a series condenser in the earth lead for the purpose of reducing the load of the earth or counterpoise. This electrically satisfactory possibility is unfortunately inadmissible from the point of view of risk from shock. In the event of the H.T. positive going to earth the full potential of the supply becomes connected between the metalwork and the microphone and telephones, the insulation of which may not perhaps be quite adequate. To reduce this danger an attempt was made to shunt the series condenser with a resistance of the order of a few hundred ohms, but the residual high-frequency voltage on key and microphone brought in complications which, in view of the wide frequency band required, chokes could not cure. In isolated cases where microphones were not used the arrangement was found practicable, but its use has been discontinued. The chief reason for abandoning it was the fact that metal cases enclosing the apparatus, and particularly mechanical remote controls, had to be insulated from earth and were a fruitful source of maintenance difficulties.

(18) Monitoring

The problem of setting up the transmitter on its allotted frequency was readily met in the early days by carrying in the aircraft some form of rough wavemeter, but the present-day requirement of accurate setting-up has rendered it practically impossible to make the necessary exact adjustments by this means.

Calibrated master-oscillator circuits are capable of giving an accuracy of ± 3 kc./sec. or thereabouts on wavelengths of the order of 50 metres, but on shorter waves the accuracy becomes insufficient. The problem would have remained unsolved, except in the case of a few preselected spot waves which can be adjusted by means of a crystal-controlled wavemeter or monitor, had it not been for the introduction of the listening-through device referred to in Part I, Section (14). This enables the operator in the aircraft to set up his receiver tuning and then to adjust his master-oscillator so as to produce an audible heterodyne in his telephones.

(19) Fatigue

The very high noise-level encountered in military aircraft, combined with discomfort caused by vibration and change of atmospheric pressure, rapidly causes fatigue. This seriously impairs aural efficiency.

Investigations have shown that a telephone output level which is amply sufficient for reception and for intercommunication immediately after leaving the ground, gradually becomes insufficient, until after an hour's flight it may be quite useless. It is possible to compensate for this by occasional adjustment of volume control, but there ultimately comes a state when serious distortion occurs and when further increase of telephone output only results in acute discomfort and unpleasant physical sensations. To this may be added the general loss of response to stimuli when oxygen has to be resorted to.

Apart from its effects in other directions, fatigue remains a serious handicap in the operating conditions of aircraft radio.

(20) Lightning

It is a remarkable fact that, although an aircraft would appear to be an ideal target for lightning, the number of occasions on which a lightning discharge has occurred in an aircraft in flight is remarkably small. Furthermore, damage due to lightning is usually slight, and fatal accidents or even serious injuries are practically unknown. Fortunately also, serious danger is eliminated by the taking of quite simple measures.

The most likely condition for a discharge through an aeroplane is when the trailing aerial is in use, for, under those conditions, the long metallic path facilitates a discharge between two clouds or parts of the same cloud. The effects of a discharge are various. An almost invariable result is the fusing of the aerial wire at a point close to the fuselage, and the consequent loss of the aerial. Another result, which is somewhat more hazardous to the aircraft, is the bursting-apart of the fairlead under the explosive force of the disintegrated aerial wire which it carries. The force of the disruption may be sufficient to occasion appreciable damage to the aircraft structure in the neighbourhood of the fairlead. A third result is the fusing of the aerial connection between the fairlead and the apparatus by way of the aerial winch. This risk is only slight, since the discharge generally takes a more direct path to earth and thence out via the propeller or wing-tips or tail. A discharge is usually accompanied by a vivid flash, which, though decidedly unpleasant and liable to singe the eyebrows and hair of the occupant, generally causes no personal injury. Quite frequently it is found afterwards that the apparatus, apart from the loss of the aerial, is still in working order.

The most serious danger attending the occurrence of lightning discharge is the possibility that vital structures and control wires may be damaged or severed by the disruption of parts such as the fairlead. In rather extreme cases extensive portions of the fuselage skin and wing coverings are blown out, thus impairing the aerodynamic properties of the craft. It will be seen, therefore, that accidents are due to secondary causes and are almost invariably limited to localized material damage.

Precautions taken against lightning include the reeling-in of the aerial when the aircraft approaches thunderclouds and when atmospherics are heard in the receiver at exceptional strength and with exceptional frequency. But since the process of winding-in is a lengthy one, it is usual to provide means for earthing the aerial before this operation is undertaken. This is facilitated by the provision of an earthed point close to the aerial clamp on the winch and means for a quick connection by the release of a catch. But although this method affords sufficient protection for the equipment and internal wiring, it does not save the fairlead from bursting. To provide this further protection implies the earthing of the aerial at a point external to the fuselage. This can be done by the provision of a short-circuiting member across a safety gap between the aerial and earth, but the mechanism involved is too cumbersome and cannot be readily standardized for all or even for a number of aircraft types. Consequently it has been deemed sufficient to provide a safety gap at a point external to the fuselage which, while of sufficient width to withstand the normal high-frequency voltages on the aerial, is readily bridged by a lightning discharge. Various forms of gaps are available, but the very nature of the case does not permit of comparison between the various types from the point of view of the protection they afford.

One class of gap employs the usual serrated edges and straight conductors to earth and to the aerial. Another class employs carbon electrodes in free air. It is believed that gas discharge tubes have also been suggested for this purpose.

Although the trailing aerial is the most usual cause of lightning discharge, there have been cases where aircraft have been struck by lightning which appears to have entered at one wing-tip and left at the other or via the propeller.

(21) Rain and Dust Static

In certain areas of the globe a particularly intense form of interference to radio reception is occasioned by the impact of charged rain and sand on the aerial. There results a continuous roar in the telephones which effectually prevents reception even of nearby and powerful stations. With the increase in receiver gain which has taken place over the last few years it is possible to ensure some sort of service by utilizing the screened loop which is frequently fitted in connection with direction-finding. This eliminates all but the most severe forms of rain and dust static, and is frequently employed.

This subject has recently received very careful attention in America, where direction-finding loops were commonly of the unscreened type. The experiments carried out in the U.S.A. are significant and show that enclosing the direction-finding loop within the fuselage gives no noticeable advantage over the external but screened loop. But the experiments, to the accounts of which the reader is referred for fuller details, reveal the fact that in the worst cases the above cure is ineffective. It would appear that the rate of charge is then so great that brush discharges occur at wing-tips and sharp edges. A cure has been suggested by the American investigators, who advocate the fitting of short trailing wires to the wings and tail and the insertion of anti-oscillatory resistances at their point of attachment to the aircraft.

PART II

DIRECTION-FINDING

It is not proposed to deal with direction-finding as such at any length; the subject would warrant the writing of a whole series of papers. Rather is it intended to bring out the peculiar features of direction-finding under aircraft conditions.

(1) Aircraft Direction-finding

(a) Loops.

Direction-finding was first applied to aircraft during the War, when aeroplanes were generally built almost entirely of wood. The earliest form was the internally-stowed loop capable of rotation on a vertical axis. On account of the low gain of the receivers then available, the loop was made of rather large dimensions and occupied a complete bay in medium-sized aircraft. These loops when associated with 7-valve amplifiers provided a very satisfactory service. They were, and all loops are still, subject to quadrantal errors occasioned by the asymmetry of the fuselage straining wires with respect to the loop. This class of error has received considerable attention in the past and many devices have been proposed and applied with a view to its elimination. The subject is too vast to treat adequately in a general survey, so reference will only be made to an attempt to strike at the root of the matter by providing short-circuited metal loops with their axes along the fore-and-aft axis of the aircraft. This intensified the effect of the structural loops encircling the fuselage and so neutralized the more powerful effect of the longitudinal structure loops. With suitable positioning of the added loops quadrantal error was substantially eliminated.

As fuselages became smaller, these direction-finding loops could no longer be installed efficiently, and another class of direction-finding aerial made its appearance. It consisted of a single-turn or multi-turn loop of flexible copper wire secured to a bandage stuck along the wings and the outer struts of the biplanes then in use. This system was not exactly a direction-finder, but was used for homing purposes by keeping the aircraft on a course giving zero signal strength from the ground station selected for homing on. This arrangement had the advantage of large effective height, or area-turns, and was later considerably improved by the addition of a smaller loop with its plane at right angles to the first, the two being connected together in accordance with the well-known scheme devised by J. Robinson. The two sets of loops were usually secured to the wings and struts throughout their full length, and gave no trouble in respect of maintenance.

With the introduction of metal wings the wing loops lost a considerable part of their effective height owing to the short-circuiting effect of the closed loops of the wing structure. To remedy this defect the bandage type of loop was replaced by a stretched copper wire of heavy gauge and suitably spring-loaded, the whole being mounted slightly outboard behind the wings. The use of this class of loop continued until the introduction of monoplanes.

The problem of direction-finding on monoplanes was studied from various angles, but in the end all attempts to apply a large loop were abandoned and the small outboard loop made its appearance. This consists of a number of turns of wire enclosed in a metal tube of circular shape and split at some point on its circumference to avoid its short-circuiting effect on the inner loop. The complete structure is mounted in such a way as to be capable of rotation about a vertical axis, and may be fitted to the fuselage or on the centre-section of the wing when applied to a biplane.

With this form of loop it is impracticable to apply quadrantal-error correction at the source. It is therefore usual to choose a position on the aircraft where this form of error is least. This is usually found at the electrical centre of the wing-fuselage formation, but is dependent on the position of the loop under or over the top wing or under the fuselage. In certain aircraft it is impossible to locate the loop in a position convenient for its operation; it is then necessary to provide remote-control mechanism, which, however, is a source of considerable trouble to the aircraft constructor and to the operator.

In recent years there has been introduced a form of external loop which, when not in use, is capable of retraction into the body of the aircraft, thus avoiding the heavy aerodynamic drag which it otherwise would cause. Although certain designs have been found satisfactory in relatively slow aircraft, this type of system cannot be said to be applicable to high-speed aircraft and particularly to military machines, where room cannot conveniently be spared for the retraction of the loop.

Notable among the many varieties of loops which have been suggested during the last few years are loops of the "radio-compass type," which enable course to be maintained by keeping a central-zero dashboard instrument on zero, and the automatic radio compass which has recently made its appearance. This class of instrument gives the bearing of the selected station directly on a 360-degree scale.

(b) Icing-up.

In recent years the problem of ice-formation on aircraft has been attacked from a great variety of standpoints, and it is desirable to mention the particular aspect of icing-up of outboard loops.

The formation of ice on the loop has two effects: one is the serious increase in drag and possible fracture of the support, and the other is the liability of the device to become jammed, thus putting the rotatable loop out of action. The danger is a particularly serious one in connection with high-speed aircraft fitted with retractable loops. Icing-up may mean jamming of the loop in its extended position, with consequent increase of drag and risk of carrying away into the tail and elevators. It would appear that, on this account, the unprotected outboard loop is doomed, for it is impracticable to provide it with suitable de-icing devices.

To overcome this difficulty it has recently been proposed to enclose a small loop, about 8 in. diameter, in a streamlined casing in which it can be freely rotated, thus doing away with most of the icing danger while regaining ease of rotation and convenience of control. This arrangement, which originated in the U.S.A., would appear to have a very promising future before it since it satisfies the more reasonable requirements of the radio-communication service without encountering fierce opposition on the part of aircraft constructors.

(c) Polarization error.

The accepted cures or palliatives for polarization error or "night error" which are used in the case of ground equipment cannot, unfortunately, be applied to aircraft. In the first place, the fitting of Adcock or spaced aerials is inadmissible from the point of view of aerodynamic forces and drag. In the second place, an aircraft is too far from being the ideal flat site which a spaced-aerial direction-finder requires for efficient performance. On such a site the effects of horizontal polarization in the structure of the aircraft are sufficiently serious to obliterate almost completely any advantages which the aerial system may possess. The only hopes at present are pulse-transmissions and cathode-ray loop reception by the time-interval method, and the use of rotating Adcock aerials or the like on the ground. In view of the importance of the subject it is hoped that radio engineers will study it attentively.

(2) Ground Direction-finding

In this section it is proposed to deal with some of the special features connected exclusively with transmissions from aircraft.

Rapid interchange of information is necessary between the several stations of a triangulation group in order that the "fix" given to the aircraft shall not demand considerable correction, to allow for the interval of time that elapses between the taking of bearings and the communication of the "fix."

(i) Aeroplane effect.

This type of error is only met with in connection with direction-finding of transmissions from a point elevated above the surface of the earth. It is akin to polarization error, but is amenable to calculation, and allowance can be made for it. It is therefore useful to treat it as a distinctive form. It has been described extensively in textbooks on direction-finding.

The nature of the error is a displacement of the bearing to the rear of the aircraft when the latter is fitted with a trailing aerial. Thus when the aeroplane is heading towards or away from the direction-finding station the error is nil; conversely, it reaches a maximum value when the aircraft flies across the line of propagation.

The error increases with the angle of elevation of the aircraft. It does not appear to be generally known that the observed bearing passes through a point on the ground in line with the effective trailing line of the aerial. This, at least, is true when the earth can be considered a perfect conductor. From this we can derive the useful rule that the aircraft's position is ahead of the reported "fix" (obtained by means of loop or similar aerials) by an amount equal to $h \cot \theta$, where θ is the effective trail angle and h is the height of the aircraft above the ground. This circumstance makes it unnecessary for the ground stations to work out bearing corrections (a complex calculation) in order that a true "fix" may be given to the operator on the aircraft.

It may be mentioned in passing that systems of direction-finding which are free from polarization error are also free from aeroplane error.

(ii) Rotary beacons.

In order to enable aircraft to obtain their positions without necessitating their carrying direction-finding apparatus and without their having to wait their turn for direction-finding from the ground, there was introduced soon after the War a beacon of the rotating-loop type.* There is provided on the ground a large loop carrying high-frequency currents and continuously rotated on a vertical axis, a complete rotation occupying 60 sec. When the "zero" of the loop is oriented towards the geographical north a characteristic signal is emitted. The operator in the aircraft starts a stop-watch at that precise instant and stops it when the "zero" reaches his direction. Six times the interval in seconds which has elapsed since the north signal occurred gives the bearing of the receiving station with respect to the transmitter. This system suffers from the general defect of polarization error, but, owing to an averaging process which appears to be involved, the errors are considerably less than are normally obtained on a receiving loop.

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* See *Journal I.E.E.*, 1928, vol. 66, p. 241; 1931, vol. 69, p. 83; 1935, vol. 77, p. 285.

It has been proposed by J. Robinson and others, and later on by R. L. Smith-Rose, to substitute an Adcock aerial for the loop on the ground and so reduce polarization error to a very low minimum. Some experimental work was done in this connection, but no developments have yet taken place. Three rotating beacons of the rotating-loop class are in use at the present day at Orfordness, Tangmere, and Rangoon, and frequently give ranges to aircraft of the order of several hundred miles. An improved form of this class of beacon was constructed in France some years ago. It comprises fixed aerial loops and goniometer or equivalent excitation, thus avoiding the necessity of rotating the complete aerial structure. This allows of greater power being used. The rotating beacon has not, on the whole, received general support, chiefly perhaps on account of the relatively long period required to obtain a "fix" from two beacons which may or may not be transmitting simultaneously.

(iii) Track beacons.

The blind-approach and blind-landing beacon originated in the U.S.A., where it has been exhaustively investigated and reported upon at considerable length, chiefly by Diamond and his associates.

The original type, which is still in use in America in considerable numbers, was applied to medium waves and consisted essentially of two loops set at an angle to each other and keyed alternately with interlock signals such as the morse letters A and N. Along the line of equal radiation from the two loops the interlocked signals appeared as a continuous dash. By keeping to the equi-signal zone the pilot of the aircraft was able to follow a predetermined course, and could thus reach the beacon without employing any other form of navigation. In practice, however, it was found essential to employ some form of compass to avoid hunting about the equi-signal line. This system has been considerably improved in recent years by eliminating the horizontal elements of the loops, which had been found to cause serious trouble at night and to aircraft fitted with asymmetrical and non-vertical aerials. Modern forms utilize vertical radiators, suitably phased, and offer the possibility of furnishing equi-signal courses in different arbitrary directions. For fuller details the reader must be referred to the original documents and papers of the Bureau of Standards, and other sources.

This system has been investigated both in this country and on the Continent, and has been found to be practically unworkable over here on account of lack of adequate channels free from broadcasting interference. In America it has been blamed for a series of accidents which are attributed to course deviations and course-splitting occasioned by stray reflections from neighbouring hills. But since the inquiry is still in progress it is too early to say whether or not the accidents are attributable to this class of radio guidance.

(iv) Blind-approach beacons.

Although some early work was done in the U.S.A. on approach beacons utilizing very short or ultra-short waves, which were thus capable of being efficiently directed in the form of beams, the first commercially successful method was devised by the Lorenz Company and is now being rapidly developed in Europe. No comprehensive paper has yet been written on this method, although its general principle and leading features have been the subject of short papers and reports. It is therefore proposed to conclude the present paper by briefly mentioning its main features.

In its original form the system comprises a track beacon and two markers. The track beacon provides an equi-signal path of interlocked dots and dashes produced by causing two reflectors, disposed on either side of a central radiator, to come into action alternately. The distortion of the polar diagram caused by the reflectors in turn is symmetrical about the line normal to the three aerials, which are in a common plane. The aerials are designed to radiate only vertically polarized waves, and therefore freedom from spurious effects is assured in the case of reception by an asymmetrical aircraft aerial.

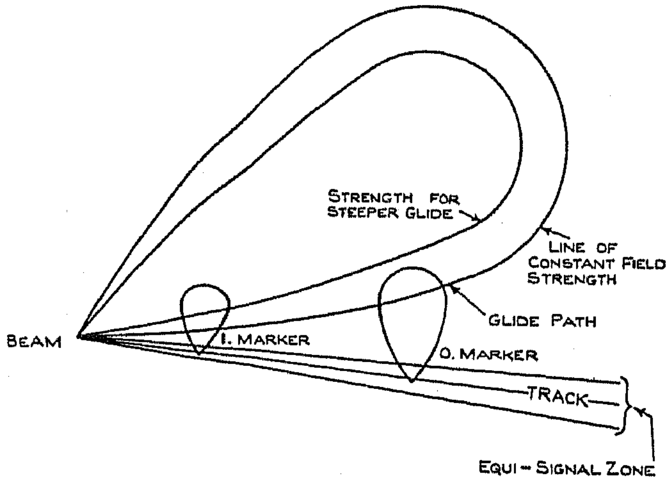

Fig. 12.—Lorenz beam.

This track beacon, working on a wavelength of the order of 9 metres, is supplemented by two markers situated respectively at the boundary of the aerodrome and 2–3 miles out. These markers operate on a common frequency, different from that of the track beacon, and are modulated at different frequencies. Their aerials are arranged to radiate mostly in an upward direction.

The installation in the aircraft consists of a vertical aerial for reception of the track beacon and a horizontal aerial for reception of the markers. The output of the track-beacon receiver is taken to headphones where the interlock signals are heard, and to a dashboard indicator where they are reproduced in visible form. The output of the marker-beacon receiver is also connected to the headphones and, through suitable note filters, to two lamps on the dashboard. One lamp indicates the transit of the outer marker while the other indicates the transit of the aerodrome-boundary marker.

Having found the equi-signal line at a distance some miles from the aerodrome, the pilot follows the received indications, keeping at a pre-arranged altitude to clear all likely obstacles. On passing the outer marker the aircraft is put into a glide which should bring it to about 50 ft. off the ground at the second or aerodrome marker. From this height it is almost invariably possible to effect a landing by sight.

Alternative forms of track beacons have been produced possessing various apparently desirable properties such as lack of radiation in unessential directions and improved characteristics enabling a radio glide path to be followed by keeping to a line of constant field-strength, as shown in Fig. 12; but it is too early to say whether these alleged advantages are real or illusory.

CONCLUSION

The author has endeavoured to refrain from describing apparatus and methods of general interest, and to keep to the specialized conditions pertaining to aviation. Much of interest has been omitted, either intentionally or through ignorance, but it is hoped that this survey has had the desired effect of calling attention to the peculiar difficulties which designers should always bear in mind when contemplating the installation or provision of new radio apparatus and devices.

ACKNOWLEDGMENTS

The author wishes to express his great indebtedness to Marconi's Wireless Telegraph Co. and to Standard Telephones and Cables, Limited, for the very kind loan of illustrations and lantern slides of obsolete and of modern apparatus, and to the Air Ministry for permission to publish certain facts and requirements not previously mentioned in published documents.

DISCUSSION BEFORE THE WIRELESS SECTION, 5TH APRIL, 1939

Major C. E. Prince: I have been much interested in comparing this paper with my own on a similar subject, of nearly 20 years ago.* It seems still true that the practical and mechanical difficulties of radio in aviation are greater than the electrical ones, or at least are the main cause of the latter. But the passing of time has brought many of the resources then only hoped for—the silent generator, the electrolytic condenser, non-microphonic valves, and so forth. The microphone problem still seems to remain; and I am convinced that there is some hidden fallacy in any attempt to get rid of noise by balancing.

I should like to put in a general plea for a certain element of crudity in aircraft radio equipment, which is very desirable in war design. Under war conditions, mechanical complexity is a great handicap. For example, could not the separate difficulties of temperature and pressure changes, and of vibration, be overcome by enclosing the whole apparatus in a case thermally insulated, pressure-tight, and suspended to counteract vibration? With regard to the last, my own experience is that it is best to separate the two factors of springing and damping, as far as it is possible to do so. For providing power, cannot the power for the radio apparatus be got from a dynamo directly driven from the engine? With fixed engines on the wings, this seems at least possible.

Mr. R. A. Watson Watt: It may be useful if, instead of commenting on any technical detail, I attempt to summarize the general factors which control the posing and the solution of the technical problems which the author has outlined.

I believe that wireless communication would, in a perfectly ordered world, be permissible only in relation to ships, to unexplored areas of the earth, and to aircraft operations; and of these three the most difficult application is the last. The explorer, it is true, requires light apparatus and has to take his power station with him, but at least he is one degree nearer to the radio-telegraphist's ideal site than is the man in the aircraft. The radio-telegraphist wants his site to be on an infinitely conducting, infinitely strong, and infinitely rigid plane; he wants his aerials to be on the top side of the plane and the rest of his apparatus to be underneath the plane (using "plane" in a geometric sense!). The aircraft engineer has the misfortune to have to work on the most unsuitable of all platforms. He works in limited space, and he is not permitted to shape that space so as to make it convenient for himself. He is limited in regard to the weight which he may use. He is not authorized to distribute that weight as he would like to do. He is limited as to the drag which he may produce against the motion of the aircraft, and in consequence of the smallness of his platform and the limitation on drag he has to use inadequate aerials. He carries his own power station, but he lacks control over it.

This platform he carries through a range of climate which the explorer would never dream of facing. The explorer may go to an extreme climate, but he has the good sense to stay in it for a substantial time. The aircraft man goes from an equatorial climate to a super-polar climate in an excessively short time. The equipment which he puts on his platform has to be operated by someone who very frequently has all the functions and much more than all the responsibilities of the operator of a one-man band. Moreover, the platform has to be prevented from colliding with other similar platforms. The function of the radio engineer in relation to aircraft is primarily to ensure the safety of the aircraft, using the term "safety" in a very wide sense. The troubles are still more acute than I have indicated; we have not merely the troubles of the individual platform and the risks of two platforms meeting, but these platforms operate in conditions of crowding which are not equalled in any maritime operations, and in which the consequences of collision are far more grave than in the maritime case.

The functions of the radio equipment are divisible into two classes. There are, on the one hand, the requirements of communication between ground and air, between aircraft and aircraft, and between the occupants of the individual aircraft; and on the other there are the technically separate requirements set by the use of the wave-field as an aid to the navigation of the vessel. Considerable difficulty is superimposed on all the other difficulties of the aircraft radio engineer by the need for two essentially independent types of service of that kind.

In present circumstances the aircraft radio engineer also has to work in an extreme hurry; indeed, every piece of equipment which he installs is obsolete before it is adopted and put in.

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* *Journal I.E.E.*, 1920, vol. 58, p. 377.

The moral of the summary which I have attempted to make is that aircraft radio is in need of a great research and development effort. The miracles of ingenuity and contrivance which have gone into such things as are described in this paper have provided only the very rudiments of an adequate communication equipment for the modern aircraft; I trust that one of the effects of this discussion will be to stimulate and intensify that very valuable co-operation between industry and user which we now enjoy, but which must be made still wider and still closer.

Mr. R. P. G. Denman: I am rather disappointed at the almost total absence of measurements from the paper. To give one example, the author alludes to the serious reduction of communication range due to the small angles taken up by a trailing aerial in flight, but he gives no numerical information on this point. I understand that photogrammetric measurements have been made by the Air Ministry and that they point to a trail angle of about 4° for a speed of 200 m.p.h. and a 250-ft. aerial carrying a $1\frac{1}{2}$-lb. weight. Aeronautical research work of this kind is less expensive for the Air Ministry than for others, and such results as have been obtained ought surely to be published in detail. Corresponding field-strength measurements would enable the effective height to be determined for various Adcock receiving conditions.

The author rightly draws attention to the necessity for compactness, emphasizing its special importance in the immediate neighbourhood of the pilot's cockpit. Already it is becoming necessary to remove from the instrument panel of an aeroplane everything that is not absolutely essential, and among these non-essential objects I include every instrument that does not need adjustment and that is capable of giving a remote indication. By taking many purely mechanical parts away from the panel and reading the instruments remotely we should be free to group the actual indicating means more compactly and in a more logical order than at present. For this reason, and because of the high degree of concentration that they would make possible, I think that cathode-ray indicators, in spite of some apparent disadvantages, will eventually earn a place for themselves on the instrument panel.

With regard to instrument landing systems, I have long believed that a glide path is both a necessary and a practicable element. Horizontal polarization and shorter wavelengths than those at present used in Europe are, however, desirable. I am convinced that the Air Ministry's policy, whereby a very considerable British commercial effort was directed into other channels, has been a mistaken one.

Wing-Commander D. H. de Burgh: I should like to emphasize the increasing difficulty with which we are faced in regard to aerials for aircraft, particularly in the Royal Air Force. Those concerned with operational requirements are continually demanding that our ranges shall increase, while those concerned with aircraft performance insist that there shall be no excrescences on the outside of the aircraft. We are therefore virtually asked nowadays to produce unlimited communication with no external aerial system, which of course is an impossibility.

I think that most engineers would like to be able to employ alternating current for aircraft installations. In the past, for reasons which the author mentions, it has not been possible to do so, but communication requirements and the multiplicity of apparatus are increasing so much that the use of alternating current should be economically possible in the future.

The author mentions the laryngaphone and similar types of microphone. We have tried them in the Air Force and at Farnborough repeatedly, without success. Nevertheless, we are continually being told that other people find such microphones satisfactory. Perhaps they do not apply such severe tests as we do, and secondly the use of a different language may come into the question.

I think that there is a misprint on page 235, where there is a reference to an 8-in. streamline form of loop. As far as the Royal Air Force is concerned, we are forced, for operational reasons, to employ the larger size of about 11 in. I mention this because I have already encountered adverse comment from aircraft engineers with regard to the size of the streamline loop which we have provided.

Mr. L. A. Sweny: I should have liked the author to include in the paper more information about the effect of ice on wing-tip-to-tail aerials. What is his opinion of the fore-and-aft aerial, and especially the twin-wire fore-and-aft aerial which seems to be coming into general use, especially in civil aviation? As regards the siting of direction-finding loops on aircraft, it is suggested, perhaps as an ideal, that the loop should be placed in the electrical centre of the aircraft. At what stage is it possible to make a rough calculation of the best possible position for the loop?

With regard to the use of the laryngaphone, the experience of the Royal Aircraft Establishment is borne out by our own. One of the reasons why the laryngaphone has been preferred abroad is that certain pilots do not like the addition of the microphone to the oxygen mask.

I notice that the author refers to the difficulty which is experienced in providing an external aerial-earthing switch for a fairlead. In our experience that has been a fairly easy matter on land machines, but of course so far as flying boats are concerned each case has to be treated individually.

With regard to H.T. supplies for receivers, there seems to be no mention in the paper of the use of anode convertors, and I should like to know whether the author has any views on that subject. The vibrator has lately become much more reliable, and it looks as though some weight could be saved by using it for H.T. supplies, at any rate for receivers.

I should like to associate myself with Mr. Denman's suggestion that more experimental work should be carried out by the Royal Aircraft Establishment with the machines that apparently are available. It is the general feeling, especially on the part of civil air transport companies, that more information might be released about wireless problems, because the Royal Air Force must meet with special conditions which are experienced in civil aviation only if very special tests are carried out.

Mr. A. J. Gill: The author mentions the use of crystal oscillators, and rather suggests that aircraft radio engineers have been waiting for the introduction of zero-coefficient crystals. This surprises me a little, because when I was at the Hague Conference in 1929 a representative of Pan-American Airways told me that on the aeroplanes operated by his Company along the American coast from North America down to South America crystal-controlled transmitters were employed working on wavelengths of the order of 30 m.

Mr. W. L. McPherson (*communicated*): While much of the material in this paper is applicable to all types of aircraft, both civil and military, stress is laid, not unnecessarily, on military requirements, and it is interesting to note how these requirements have in various ways directed development in other directions than those evident in development for civil aviation purposes. Two particular cases may be quoted. One is the rather deprecatory attitude adopted towards the use of crystal control, based on the grounds that the feature of being rigidly tied to a preset wavelength—a feature which in many quarters is regarded as highly desirable, perhaps even essential, for successful commercial operation—may become a disastrous limitation under war conditions. A second is the emphasis laid on the noise problem in the citation of a noise level of 135 phons. Nothing like this has to be dealt with in commercial machines, and one can only commiserate with the pilots and operators subjected to such a bombardment.

The greater part of the paper is concerned primarily with the factors which influence the design of radio equipment for use in aircraft, and comparatively little is said about the use to which such radio equipment may be put. If one may judge from the amount of space devoted to it, the navigational use of radio as exemplified by direction-finding is regarded by the author, viewing the matter from the R.A.F. standpoint, as of comparatively small importance relative to the requirements of communication pure and simple. In the case of commercial aircraft, the importance of the navigational aspect is now fully as great as that of communication—it is hardly possible to imagine the establishment of either the transatlantic or the transpacific commercial service without the aid of radio direction-finding—and with the steadily increasing range required of certain types of military aircraft it seems inevitable that in this sphere also the application of radio to navigational purposes will ultimately assume far more than secondary importance.

A particular application of radio to navigational uses which has not been mentioned by the author, but which is likely to be of great value for military as well as civil purposes, lies in the field of height-indicating. The ordinary altimeter does not measure height; it measures barometric pressure, and can be used to estimate height above a reference level by means of calibration depending on local weather conditions and therefore subject to change. The height above this reference level may be very different from the actual height above ground over which an aircraft is flying, but of this the barometric altimeter gives no indication whatever, and when flying under conditions of bad visibility, over unknown country, the aircraft may suddenly find itself dangerously near the ground, particularly in the proximity of mountain ranges.

An instrument with a response indicating directly the height above the actual ground, therefore, should be of great value. The acoustic depth-sounding devices now fitted on many ships are of this nature, their response being proportional to the time taken by a signal emitted from the ship to return to the ship after reflection from the bed of the sea. Such devices are not readily applicable to aircraft, but ways are now being found of applying the same principle by using radio waves rather than acoustic waves. Since the velocity of radio waves is much greater than that of acoustic waves—186 000 miles per sec. as against 0·2 mile per sec.—the time-interval is too short to be measurable with the required accuracy, and recourse is therefore had to the measurement of some change in the character of the signal proportional to the length of path. An example of such an altimeter system has been demonstrated in America during the last 12 months. In this altimeter the emitted signal is frequency-modulated, and the change in signal character, used to measure the height, is the average instantaneous difference in frequency between the emitted wave and the wave received after reflection from the earth. The equipment operates on a frequency of several hundred megacycles per sec., and is reported to give accurate readings at heights as low as about 10 ft. Experimental work on a rather similar system also is proceeding in Japan, and elsewhere studies are being made of altimeter systems which likewise use ultra-short-wave emission, but measure the height by reference to the change in phase of the carrier or of any modulation imposed on the carrier.

Mr. N. F. S. Hecht (*in reply*): Major Prince points out that there has been a gap of nearly 20 years between the first and second attempts to describe the nature of aircraft radio-installations and the problems which arise and require to be solved. Perhaps it could be taken that Major Prince introduced the era of rule-of-thumb and expediency which is about to come to an end, to be replaced by treatment of a more scientific character. In this sense the present paper may be taken as a rough record of the methods of the *ad hoc* designer; future papers will perhaps deal with methods and equipment more satisfying to the critical mind.

While it is perhaps still true that the mechanical difficulties which arise in aviation radio are greater than the electrical ones, it is rather more correct to say, as Major Prince remarks, that the electrical difficulties are mainly caused by the restrictions of a mechanical or physical nature which impose themselves on the designer. There is, for instance, the case of the mask-microphone, the form of which is more or less dictated by physical considerations. In this connection I feel, with Major Prince, that the idea of suppressing noise by balancing is a fallacious one.

As regards simplicity of design for military purposes, it is an unfortunate state of affairs that those who can least afford to work complicated sets in times of stress are, for various reasons, forced to demand extreme flexibility of purpose. This condition tends to explain the difference between certain civil equipment and most military gear.

As regards the proposal to enclose the whole of the radio apparatus in a radio chamber providing all the protection quoted by Major Prince, at one time this scheme received serious consideration. It has had to be abandoned on account of lack of space and the impossibility of allotting a given " space " to radio equipment, which must dovetail as much as possible with other items of equipment and armament.

Regarding the suggestion that it would be best to separate the resilient from the resistant factors in elastic suspension, I must of course agree with Major Prince in principle; but the designer should be forgiven for using such a simple medium as braided rubber and other similar devices.

In reply to Major Prince's question dealing with engine-driven generators, these are of course normal practice for the general electric supply, but, since vital radio services have to carry on when the engines have stopped, it is still necessary to carry central accumulators. As explained in the paper, such accumulators cannot be used directly on the wireless sets in military aircraft.

I must thank Mr. Watson Watt for stating the case of the aircraft radio engineer so clearly. I share his hope that the present paper will have the effect of intensifying the co-operation of the industry in alleviating the difficulties of the engineer responsible for installing, in an aircraft which he has not planned, apparatus which he has not been allowed to shape to his own views.

Mr. Denman is rather disappointed at the lack of "measurement data" in the paper. I must agree, of course, that the reader is given very little information of a precise character which would enable him to design and lay out equipment for any specific case. The purpose of the paper was not, however, to give design data but merely to call attention to most of the unexpected difficulties and pitfalls which the designer and installation engineer will have to contend with while gaining experience.

Fundamentally the laws of radio still apply on aircraft, and an engineer with no aircraft experience is quite capable of laying down his electrical constants and calculating others. The degree of success which he achieves will depend on his knowledge or appreciation of the conditions and restrictions imposed by the "platform" referred to by Mr. Watson Watt.

Mr. Denman inquires about photogrammetric data in the possession of the Air Ministry, and quotes certain data for a given aerial. The aerial specified by him would have an initial trail angle of approximately 14°, but this is not a true measure of the effective-height factor. As explained in the paper, the aerial falls away rather rapidly towards the end, i.e. near the weight, thus increasing the above factor. The total height of an aerial made up of 0·06-in. diameter wire and used under the conditions specified would be 65 ft., giving an effective height of about 9 m. The effect of the weight of the bob on the shape of long aerials is very slight. It would be possible to produce a chart giving aerial shape and other factors from data now available, but in these days of fixed aerials is it really worth doing? Given the aerial shape, the rest is almost entirely a question of geometry; and the effective height is more readily and, I would assert, more accurately obtained by this method than by measurements on a vertical aerial on the ground. In his reference to Adcock aerials I presume Mr. Denman has in mind the signal strength obtained in such a system when receiving from a trailing aerial. In this connection it should be noted that the field strength will not be the same for all attitudes of the aircraft except at short distances. At distances of the order of 100 miles or more the atmospheric ray will be stronger behind the aircraft than ahead of it. This is readily appreciated from a consideration of the greater "broadside" provided aft as compared with that provided ahead of the aircraft. At very short distances the reverse would be the case, since the aerial is viewed more or less end-on from behind.

I do not see how cathode-ray indicators can find a use on an aircraft instrument panel except in the case of cathode-ray direction-finders and repeaters, but even then I would expect their bulk and length to be greater than those of more conventional indicators. This view would of course have to be modified if very short tubes of useful diameter were to become available.

Mr. Denman, if I understand his final remark, criticizes the Air Ministry for adopting one particular type of blind approach system, i.e. the vertically polarized type. I am afraid I am not in a position to reply to the criticism, which does not, to my mind, fairly arise from the present paper, but I think I may be allowed to say that all likely types and systems are either under test or under consideration.

Wing-Commander de Burgh raises the question of alternating currents for aircraft radio and general supply. While I am in agreement with him that alternating current should be economically utilizable in the future, I think it is correct to say that, taking into account weight and bulk of accessory components such as transformers, chokes, filters, etc., the alternator cannot compete with the d.c. generator unless and until a general load of the order of 5 kW is demanded by the whole of the services.

Regarding the remark respecting the 8-in. loop, I should perhaps explain that the proposal referred to came from the United States. R.A.F. requirements demand a larger loop, as indicated by Wing-Commander de Burgh.

Mr. Sweny asks for information on the wing-tip-to-tail aerial and its liability to collect ice. There is a lack of precise information on this question, as well as on the question of ice on aerial wires. Experimental work is proceeding, but the subject is a difficult one to tackle experimentally. In general, it may be said that ice is more liable to form on cross-wind wires, and when formed is more likely to cause fracture than in the case of fore-and-aft wires. In this respect the fore-and-aft (including the twin) aerial is to be preferred. This question, however, has to be considered in conjunction with other requirements such as, for instance, the capacitance of the aerial in small aircraft. There is at present, so far as I am aware, no standard rule for locating the direction-finding loop so as to keep quadrantal error at a low figure. The best position, which in any case must be a compromise, can only be determined by trial on the finished aircraft, and for the present only an experienced engineer can find such a position after one or two trials. I am sorry I cannot give a useful answer to the question. As regards the question of the aerial-earthing switch on the fairlead, I think the point is that no one can say whether a design is satisfactory until it has been proved, and this is not easily done. Perhaps scale models and e.h.t. discharges may help, but so far no information on this matter is available.

As regards Mr. Sweny's remarks on the subject of anode convertors and vibrators, I would refer him to Section (4)(*c*) of the paper, which touches on both those points.

Regarding the experimental work done by the Royal Aircraft Establishment, there is a regular programme of work entirely directed to the needs of civil aviation. I have no doubt that the Air Ministry would be pleased to consider any special investigation which was brought to its notice and for which there was sufficient justification to direct the spending of greater efforts. Flying facilities are far from being unlimited, however, and the simplest investigation or scheme of measurements takes a considerable time to complete.

Mr. Gill raises the question of crystals and their belated introduction in aviation. While it is correct to say that crystals of normal temperature-coefficient were in fairly regular use in the U.S.A. some years ago, it must be admitted that they were used on a limited number of frequencies. The generalized use of crystals over a large band of frequencies is quite another matter. Also, the provision of a thermostatically controlled oven raises difficulties when several crystals have to be available instantly, or when they have to be exchanged.

I wish to thank Mr. McPherson for his useful contribution to the discussion. In reply to his criticism regarding the lack of operational information, this is a matter which requires special treatment, and I have no doubt that we shall soon have a full treatment of this aspect of the question from the point of view of civil aviation.

I fully appreciate Mr. McPherson's remarks regarding direction-finding, and perhaps I should add that the importance of the subject is not to be measured by the amount of space devoted to it. The fact is that the technical difficulties in this connection are not great. Apart from quadrantal error, icing-up of loops, and remote control, all mentioned in the paper, there is little that differs technically from the general case of the receiver.

As regards radio-altimeters, these devices were non-existent—outside certain laboratories—at the time the paper was written. I agree that such an instrument, when perfected, will be of enormous advantage to the navigator and to the pilot.

INSTRUMENTS INCORPORATING THERMIONIC VALVES, AND THEIR CHARACTERISTICS*

By E. G. JAMES, B.Sc., Ph.D., G. R. POLGREEN, B.Sc., Member, and G. W. WARREN, B.Sc.

(*Paper first received* 13*th September, and in revised form* 8*th December,* 1938; *read before the* METER AND INSTRUMENT SECTION 6*th January, and before the* NORTH-WESTERN CENTRE 14*th March,* 1939.)

SUMMARY

In the first part of the paper the authors discuss the main valve characteristics which are of importance in instrument design, and describe types of valves specially designed for instrument purposes.

The principles are outlined of the various types of valve instruments for the measurement of alternating voltages (including "slide-back," peak, grid-leak, and anode-bend voltmeters), and of voltmeters and electrometers for direct voltages; and methods of measuring very small values of current and power are described. Reference is also made to other applications such as harmonic analysis, frequency measurement, and the measurement of physical quantities.

The paper concludes with a brief comparison between valve-operated and other types of instrument and indicates possible future lines of development.

(1) INTRODUCTION

The thermionic valve has long been recognized as a useful tool in almost every branch of science and engineering, but, although experimenters have realized the possibility of using valves for measurement purposes, engineers have until recently, and not without some justification, regarded the valve as being rather an unknown factor, and have been reluctant to rely on such devices for precision measurements.

During the past few years, however, several instrument makers have put on the market instruments incorporating thermionic valves which are capable of satisfying the two important requirements, accuracy and reliability. This has been made possible, on the one hand, by the instrument makers, who have designed apparatus in such a manner that variations in valve characteristics and supply voltages are automatically compensated, and, on the other hand, by the enormous improvements both in uniformity and in stability of valve characteristics which have been effected in recent years. Furthermore, the progressive valve manufacturer of to-day not only produces valves on a mass-production basis for radio-communication, but is also aware of other applications and supplies valves having the particular characteristics necessary for various types of instrument.

It is not proposed to describe in this paper all the possible methods of using valves for measurement purposes, or to consider the design of amplifiers and oscillators which are frequently used in conjunction with measuring instruments. The authors have limited the scope of the paper so as to include those instruments in which the thermionic valve is an essential component and which either provide the only means of carrying out a particular measurement or possess definite advantages over alternative forms of instrument.

(2) VALVE CHARACTERISTICS

The factors in a valve which may be of importance in determining the characteristics of an instrument are (*a*) the relationship between output current and input voltage, (*b*) the input impedance, and (*c*) stability of the characteristics.

(a) Output-current/Input-voltage Characteristics

The shape of the curve relating anode current to anode voltage of a diode is shown in Fig. 1. The "tail," AB, of the characteristic, obtained when the anode is at a sufficiently negative potential with respect to the cathode, is exponential and obeys the equation

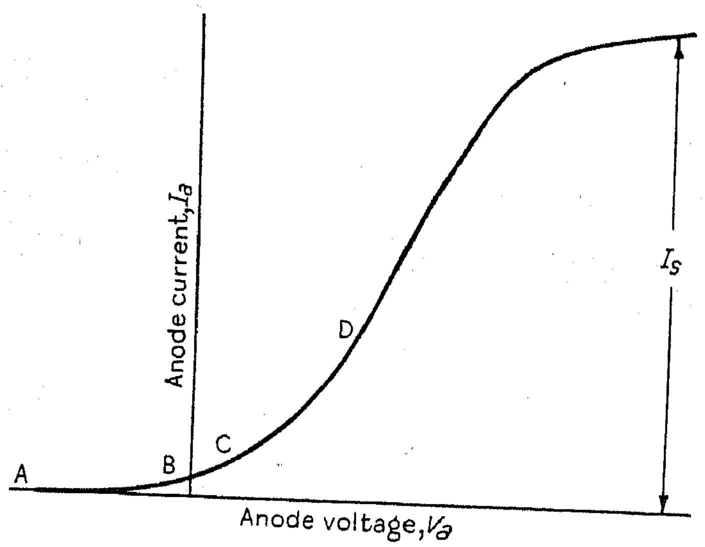

Fig. 1.—Anode-current/anode-voltage characteristic of a diode.

$$I_a = I_s \epsilon^{e(V_a+v)/k\tau}$$
$$= I_s \epsilon^{K(V_a+v)} \qquad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where I_s is the total emission of the cathode, in amperes; V_a is the voltage of the anode relative to the cathode; v is the contact potential-difference between anode and cathode; e is the electronic charge ($1 \cdot 59 \times 10^{-19}$ coulomb); k is Boltzmann's constant ($1 \cdot 37 \times 10^{-23}$ joule per degree); τ is the absolute temperature of the cathode; and $K = e/(k\tau) = 11\,600/\tau$.

Over the portion CD of the curve, the current obeys the space-charge law

$$I_a = A(V_a + v)^{3/2}$$

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* Communication from the staffs of the Research Laboratories of The General Electric Company, Ltd., the M.O. Valve Company, Ltd., and Salford Electrical Instruments, Ltd.

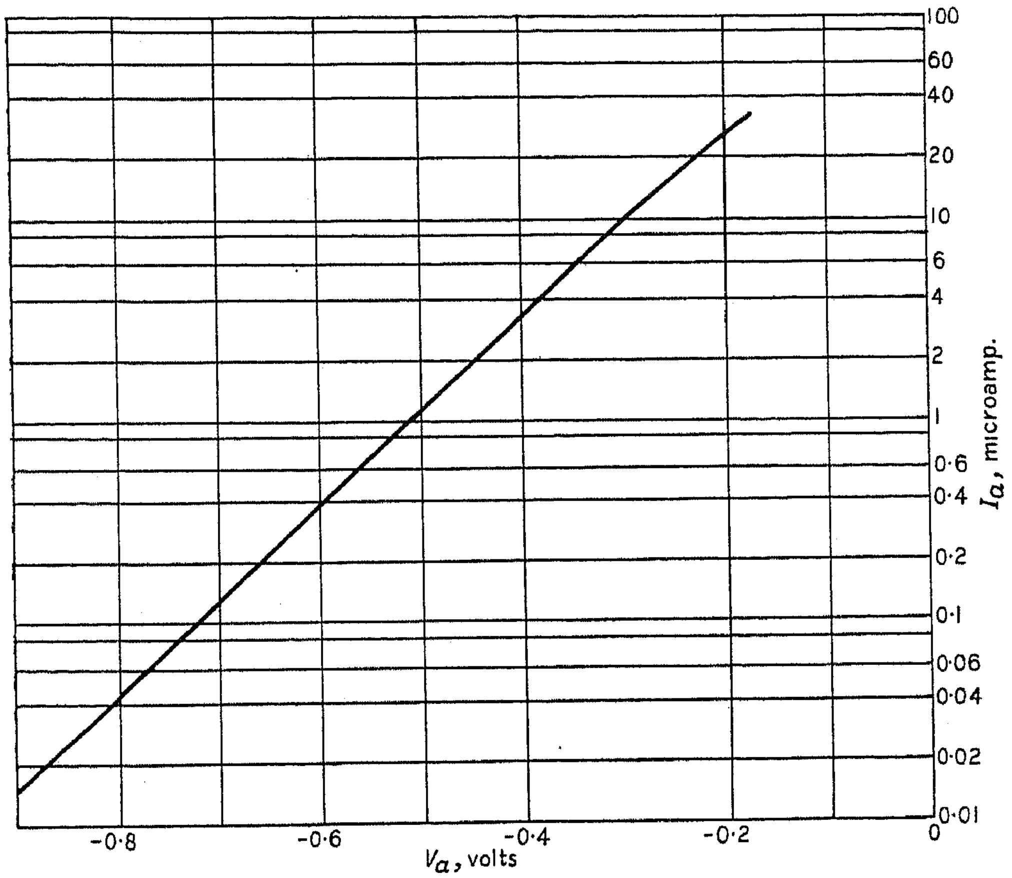

Fig. 2.—Anode-current/anode-voltage characteristic of diode Type D63.

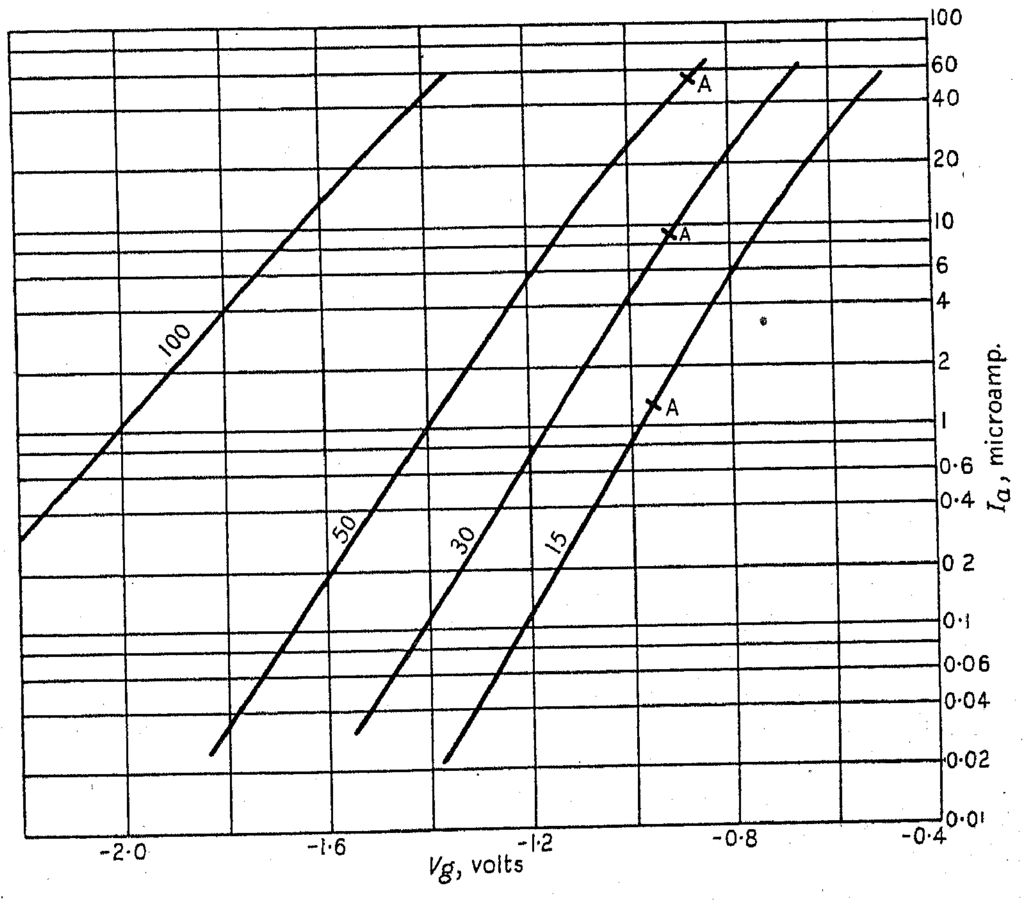

Fig. 3.—Anode-current/grid-voltage characteristics of triode Type H63.

Numbers on curves give values of V_a in volts.

where A is a constant depending on the geometry of the electrode system.

At some part of the curve between B and C the curve is approximately parabolic, while beyond D the curve becomes linear and then bends over to the saturation value of the current, I_s.

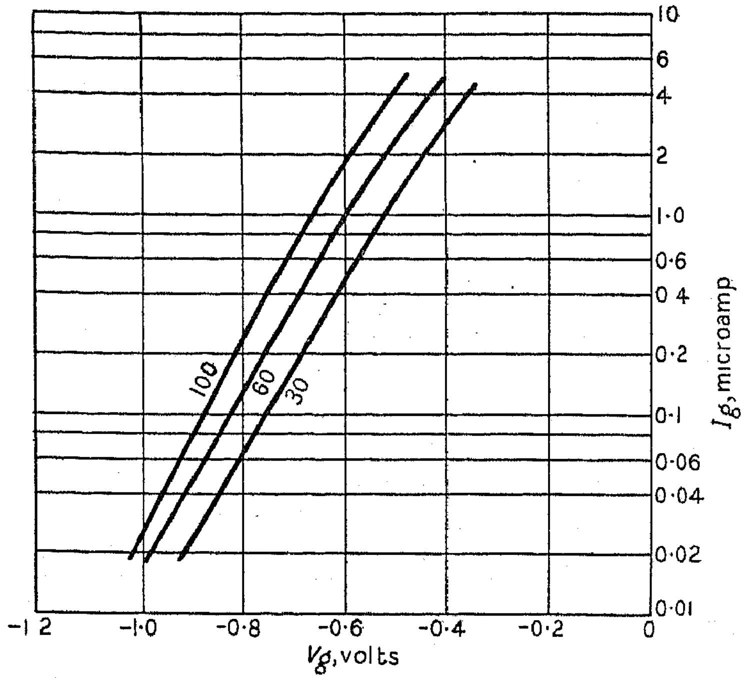

Fig. 4.—Grid-current/grid-voltage characteristics of triode Type H63.
Numbers on curves give values of V_a in volts.

The general shape of the anode-current/grid-voltage characteristics of triodes, tetrodes, and pentodes is similar to that of the diode characteristic but displaced relative to the axis $V_g = 0$ by an amount depending on the anode or screen potentials and the constants of the valve.

Use is made of the exponential characteristic in slide-back voltmeters, grid-leak voltmeters, and logarithmic voltmeters, while the square-law characteristic is important in the design of anode-bend voltmeters, wattmeters, and harmonic analysers.

The range over which the various relationships—exponential, parabolic, etc.,—hold, depends on the geometry of the electrodes. Thus the smaller the distance between anode and cathode of a diode, or between grid and cathode in the case of triodes, tetrodes, and pentodes, the greater will be the value of current below which the curve is exponential. From equation (1) it follows that, if $\log I_a$ is plotted against V_a, the curve will be a straight line with a slope $K = e/(k\tau)$. The normal operating temperature of a modern oxide-coated cathode is approximately 1 000° K., so that the theoretical value of K is 11·6. Fig. 2 shows $\log_{10} I_a$ plotted against V_a for the diode Type D63, and it will be seen that the exponential characteristic holds for currents up to 20 microamp., the actual value of K, deduced from this line, being 11·0, which is in close agreement with the theoretical value. Fig. 3 shows the anode-current/grid-voltage characteristics of a triode, Type H63, for anode voltages between 15 and 100 volts. The pitch of the grid winding and the grid-cathode distance are small in this triode, and it will be seen that the curves are exponential up to currents of about 10 microamp., but that the value of K decreases from 9·6 at $V_a = 15$ volts to 6·3 at $V_a = 100$ volts. This decrease is due to the field near the cathode becoming less uniform as the anode potential is increased, and would be even more noticeable in a valve with a lower amplification factor. The grid-current/grid-voltage characteristic for the Type H63 triode is shown in Fig. 4; the curve is exponential up to about 1 microamp.,

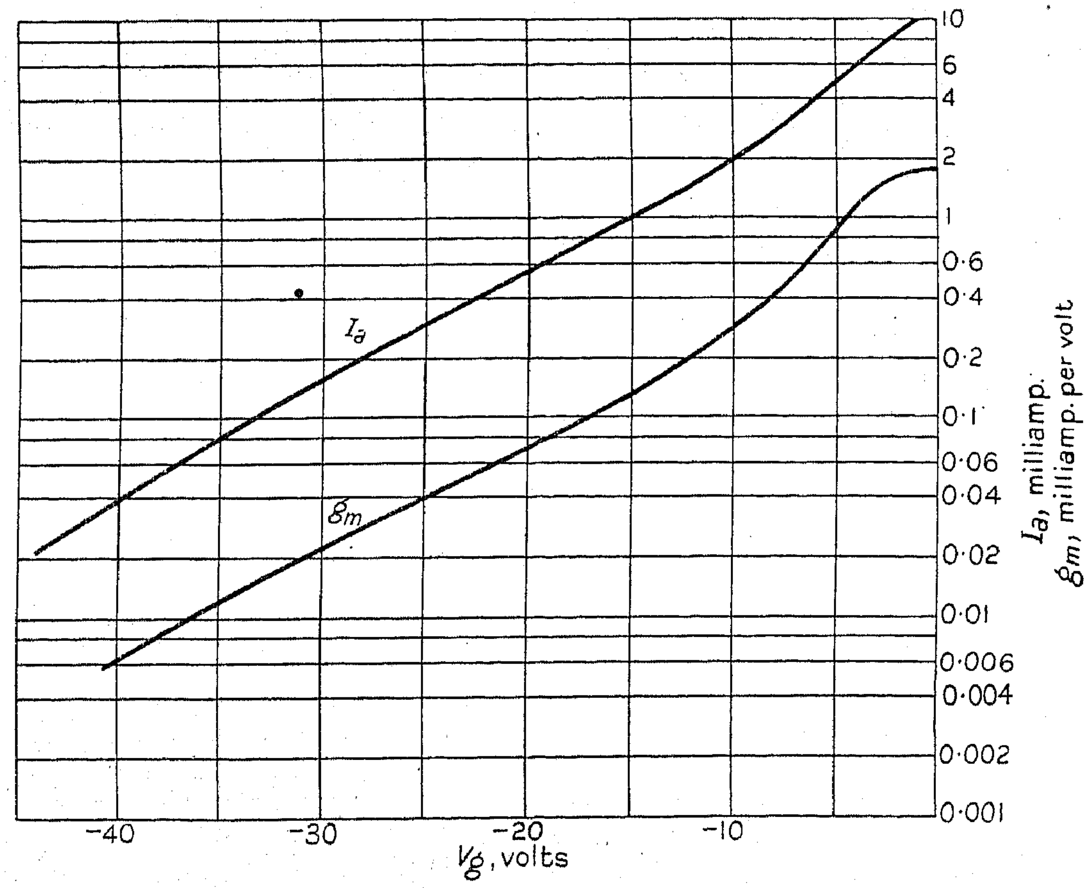

Fig. 5.—Anode-current/grid-voltage and mutual-conductance/grid-voltage characteristics of pentode Type W63.

and here again the value of K decreases as the anode voltage is increased.

The above "retarding field" exponential characteristics were obtained with a valve in which the grid pitch was uniform over its entire length. The grid can, however, be wound with a variable pitch such that the anode-current/grid-voltage characteristic is approximately exponential for a large range of grid bias: that is:—

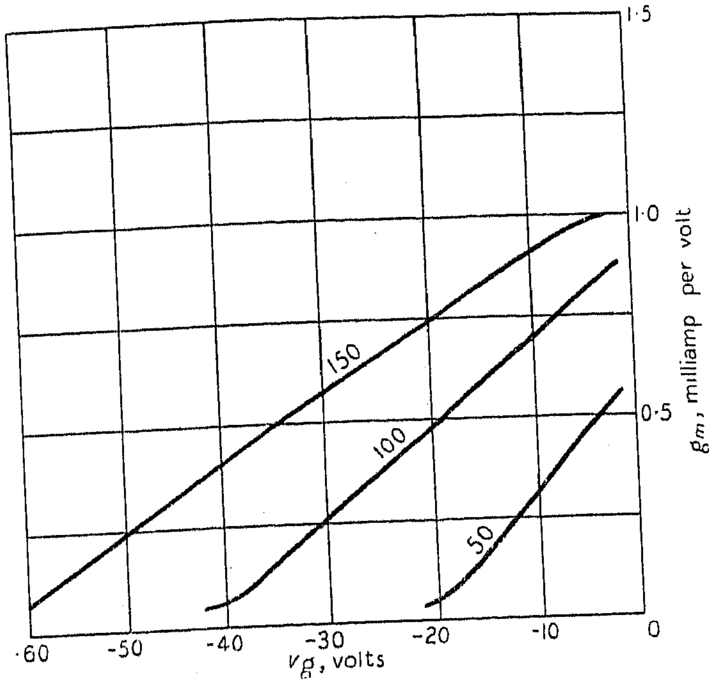

Fig. 6.—Mutual-conductance/grid-voltage characteristics for triode Type LS.5A ($\mu = 2·5$).
Numbers on curves give values of V_a in volts.

$$I_a = N\epsilon^{bV_g}$$

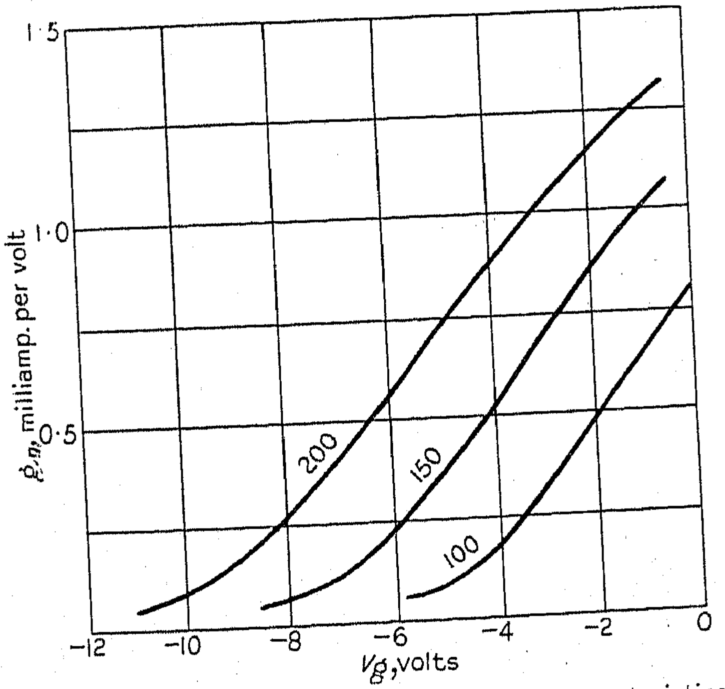

Fig. 7.—Mutual-conductance/grid-voltage characteristics for triode Type LS.5B ($\mu = 20$).
Numbers on curves give values of V_a in volts.

and the mutual conductance

$$g_m = \frac{\partial I_a}{\partial V_g} = Nb\epsilon^{bV_g}$$

Fig. 5 shows the anode current (I_a) and mutual conductance (g_m) plotted against grid bias for a W63 valve. The curves are approximately exponential for values of bias above 5 volts.

The range over which the anode-current characteristic is parabolic is very limited in diodes and in triodes having close-wound grids, but with valves in which the grid pitch is large (generally valves with low amplification factor), the range may be quite considerable, particularly when the valve is operated at high anode voltages. This is probably due to the fact that in such valves the grid is not only exercising space-charge control at the cathode surface but is also, over this part of the characteristic, acting as a shutter and limiting the area of the cathode from which electrons are escaping. This point is illustrated in Figs. 6, 7, and 8.

Figs. 6 and 7 show the mutual conductance (g_m) plotted as a function of grid bias for Types LS.5A and LS.5B. These are two triodes of similar design except for the grid pitches, which are 3·65 mm. and 1·06 mm., giving amplification factors of 2·5 and 20. It will be seen that the range of g_m over which the g_m/E_g relationship is linear, and therefore the I_a/E_g characteristic parabolic, is greater in the valve with low amplification factor and at high values of anode voltage. Fig. 8 shows similar curves for Type A577 (designed for use in valve voltmeters, $\mu = 6$), which has an indirectly heated cathode.

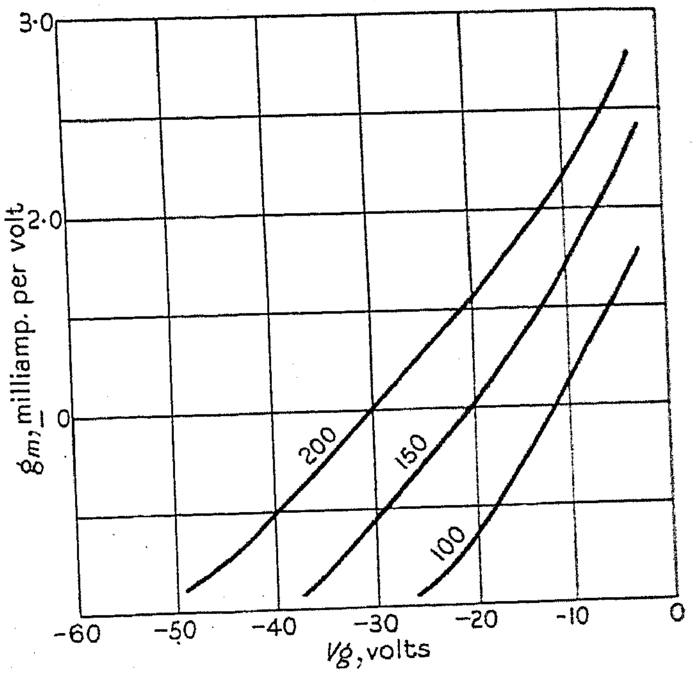

Fig. 8.—Mutual-conductance/grid-voltage characteristics for triode Type A577 ($\mu = 6$).
Numbers on curves give values of V_a in volts.

(b) Input Impedance

The factors affecting the input impedance of a valve are electron and ion convection currents in the grid circuit, the capacitance between the grid and the other electrodes, and, at very high frequencies, the inductance of the leads to the electrodes and the finite transit-time of electrons between the electrodes.

The static grid-current/grid-voltage curve for a triode is itself the sum of several curves due to different causes, chief amongst which are: (i) the electron current from cathode to grid, which has been mentioned earlier and is an exponential function of the grid voltage under

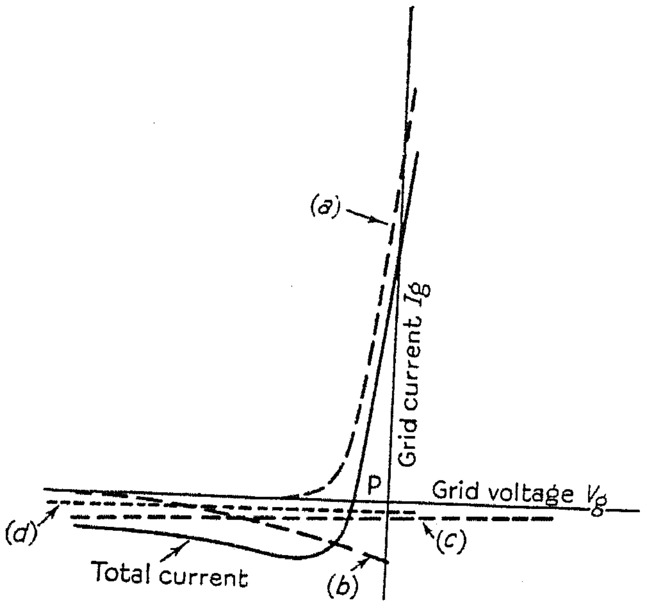

Fig. 9.—Grid-current/grid-voltage characteristics of a triode.

(a) Electron current.
(b) Positive-ion current.
(c) Leakage current.
(d) Grid-emission current.

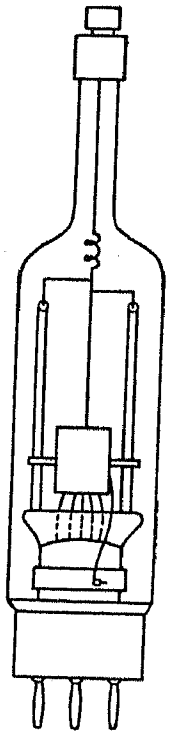

Fig. 10.—The electrometer triode.

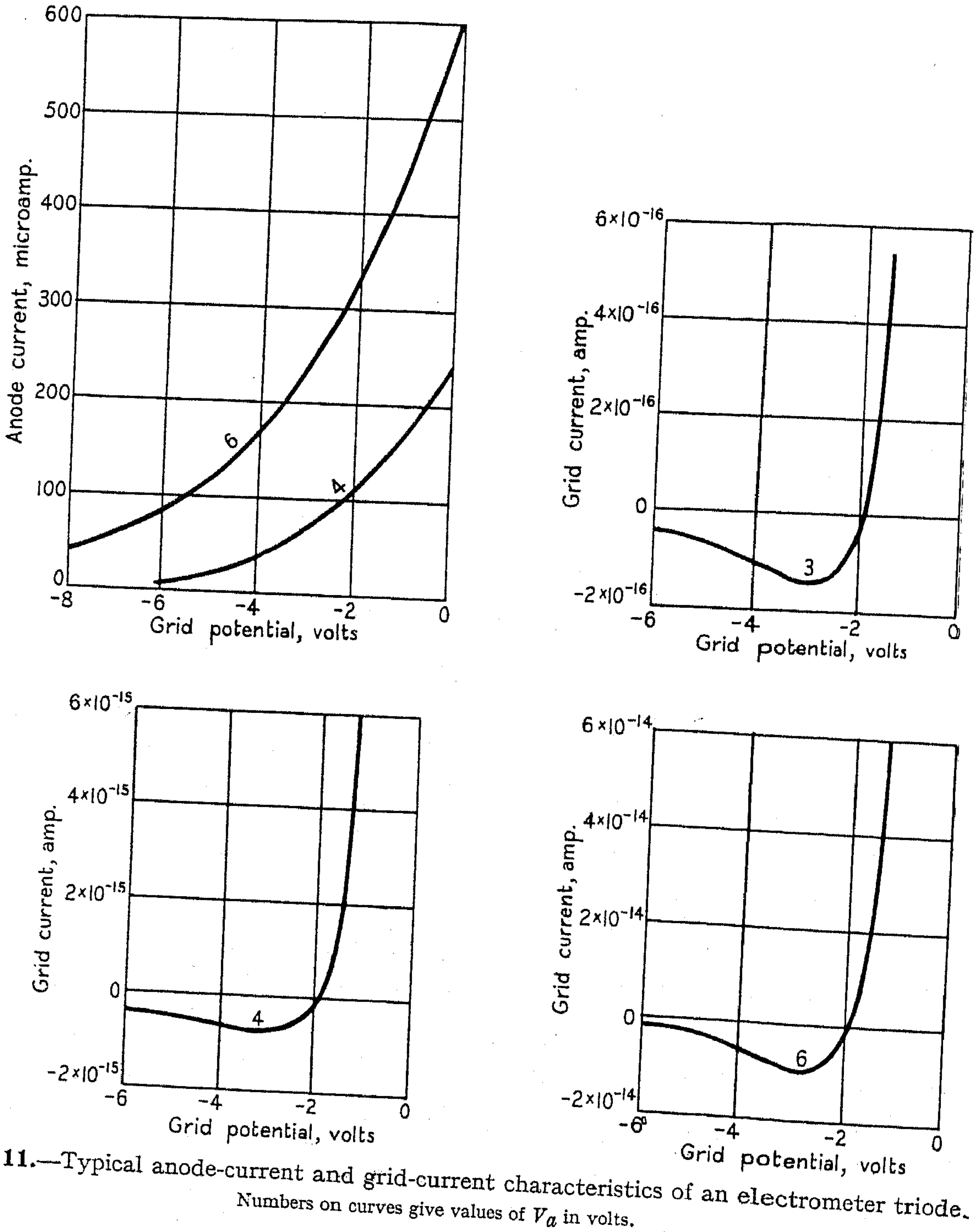

Fig. 11.—Typical anode-current and grid-current characteristics of an electrometer triode.

Numbers on curves give values of V_a in volts.

normal operating conditions; (ii) positive-ion current due to residual gas in the valve; (iii) leakage currents across insulators separating the electrodes; and (iv) emission of primary electrons from the grid. Fig. 9 shows the shape of the current/voltage curves due to these causes together with the resultant grid-current characteristic. In the type of valve likely to be used for instrument purposes the maximum negative grid current is usually less than 0·1 microamp. and the insulation resistance exceeds 10^9 ohms.

Although the grid current in standard valves, when the grid is negative with respect to the cathode, is sufficiently low for most measurement purposes, considerably lower values are necessary when it is desired to use the valve as an electrometer. By special choice and design of the supporting members of the grid and by operating the anode at a potential considerably lower than the ionization potential of any residual gas, it has been possible to eliminate almost entirely the leakage and ionization currents. Other factors which may contribute to the grid current, such as ions from the cathode and anode and photo-electrons from the grid, have been reduced to a minimum by suitable choice of electrode materials and by operating the valve in the dark. Valves of this type have been described by Metcalfe and Thompson* and by Warren.† Fig. 10 shows a drawing of one type of electrometer triode. Typical anode-current and grid-current characteristics are shown in Fig. 11.

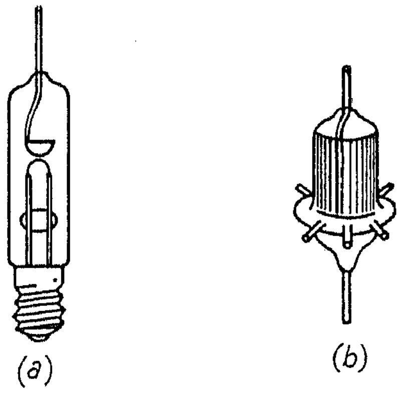

Fig. 12

(a) Type A373.
(b) "Acorn" type valve.

Low input capacitance is important in some electrostatic measurements, and in the case of the electrometer triode, mentioned above, the input capacitance is 2 $\mu\mu$F. In a.c. measurements, the input capacitance must be small in order that its impedance may be large in comparison with that of the source. In standard types of valves this capacitance is about 10 $\mu\mu$F.

When the frequency of the voltage to be measured is very high, the inductance of the connection between the source and the electrodes may have appreciable reactance. This inductance forms a series circuit with the input capacitance, so that the voltage across the electrodes may be considerably higher than that of the source. For the error to be less than 0·1 %, the operating frequency must not exceed about 3 % of the resonant frequency of this series circuit, or for 1 % error about 10 % of the resonant frequency.* Since the length of the connecting leads cannot be reduced indefinitely, the maximum frequency at which a voltmeter can be used with any accuracy is determined by the smallness of the valve input-capacitance. The diode offers the greatest possibility of low input-capacitance, and in Type A373, shown in Fig. 12(a), the input capacitance has been reduced to 0·4 $\mu\mu$F, and the leads are as short as possible. The impedance error with this diode is about 1 % at 100 Mc./sec. In valves of the "acorn" type [Fig. 12(b)] the input capacitance is about 3 $\mu\mu$F, and the impedance error at the same frequency is about 4 %.

Dielectric losses in the input capacitance of a valve will affect the power consumed from the source, but of far greater importance at very high frequencies are effects arising from the physical size of the valve. If the transit-times between cathode and grid and between grid and anode become comparable with the period of the high-frequency voltage, the current will not vary in phase with the grid voltage and appreciable power will be absorbed from the source. Power will also be absorbed owing to coupling, inside the valve, between the input and output circuits: this effect depends on the size of the inter-electrode capacitances and on lead lengths.

Table 1

Type	Mutual conductance (mA/V)	Input resistance (ohms)
KTW63	1·5	13 000
KTZ41	7·5	2 000
ZA1	1·4	50 000

In the "acorn" type of valve, the smallness of the structure reduces to a minimum the transit time, inter-electrode capacitances, and lead inductances, so that the valve is very suitable for use in high-frequency voltmeters. Table 1 gives the values of the input resistance of various types of valves at 40 Mc./sec.

(c) Stability of Characteristics

Although the uniformity existing between the characteristics of valves of the same type may not be as good as the instrument maker might wish, the modern valve gives a very stable performance during its life, particularly under the operating conditions imposed in measuring devices. The valve manufacturer usually subjects valves required for this purpose to a long ageing treatment, often as much as 100 hours, in order to stabilize the cathode emission and the contact potential differences between electrodes, since any drift in characteristics due to these factors is likely to be greater during the first few hours of operation than subsequently.

The stable operation of a device employing a thermionic valve depends not only on the stability of the valve characteristics but also on the constancy of the applied voltages. In the case of an amplifier, any changes in gain due to changes in the valve characteristics or in the applied voltages can be reduced to a large extent by applying negative feedback to the amplifier valves.

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* See Bibliography, (1).

† Ibid., (2).

* See Bibliography, (3) and (4).

The principle of feedback is illustrated in Fig. 13, which shows a schematic diagram of an amplifier where a fraction (β) of the output is connected in series with the input. If m is the amplifier gain without feedback, m_1 the amplifier gain with feedback, E_2 the output, E_0 the input without feedback, and E_1 the input with feedback to give the same output, then

$$m = \frac{E_2}{E_0}$$

and
$$m_1 = \frac{E_2}{E_1} = \frac{E_2}{E_0 + \beta E_2} = \frac{m}{1 + m\beta}$$

i.e. the gain of the amplifier with feedback is reduced in the ratio $1/(1 + m\beta)$.

Any variation in the valve characteristics or variations in the applied voltages will give rise to a change in the amplification. Let δm be the change in gain due to any of the above causes without feedback and δm_1 the corresponding change with feedback. Then*

$$\frac{\delta m_1}{m_1} = \frac{\delta m/m}{1 + m\beta}$$

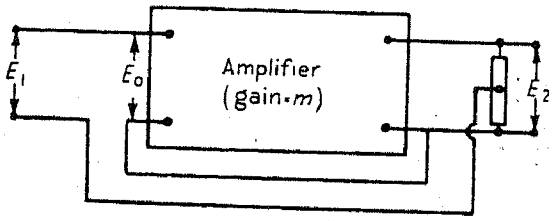

Fig. 13.—Schematic diagram of degenerative amplifier.

That is, the percentage change in the amplification is reduced by an amount corresponding to the reduction in the amplification. If $1/m << \beta$, the gain $m_1 \simeq 1/\beta$, i.e. the amplification is almost entirely independent of the circuit.

Feedback can be applied to an amplifier in various ways. The simplest method, and that usually adopted in instruments, is to include a resistance in the cathode lead of the valve. Examples are given later in the paper.

(3) ALTERNATING-CURRENT VOLTMETERS

Of all valve measuring devices, the valve voltmeter seems to be the most widely used instrument, especially for high-frequency measurements. Its popularity lies in the fact that it is sensitive and that it can be designed to absorb negligible power from the source. The type of voltmeter to be used in any particular case depends on the wave-form of the voltage, on the value required (peak or r.m.s.), and on the frequency at which the measurement has to be made.

All a.c. voltmeters are essentially rectifiers, and in the following description are classified according to the method of rectification.

(a) " Slide-Back " Voltmeters

(i) " Slide-back " type using hard valves.

The simplest type of valve voltmeter is the " slide-back " type, in which a triode or other multi-electrode valve is used as a threshold indicator. The valve is biased until the anode current is very small, and the bias is measured by a d.c. voltmeter. The alternating voltage to be measured is then applied to the grid of the valve, in series with the bias voltage, and the bias increased until the current is reduced to its original value. The difference between the two readings of the d.c. voltmeter gives a measure of the peak value of the alternating voltage: the exact relationship may be determined by a study of the valve characteristic.

With small currents, the anode-current/grid-voltage characteristic for a triode with a close-wound grid is given by

$$I_a = N\epsilon^{KV}$$

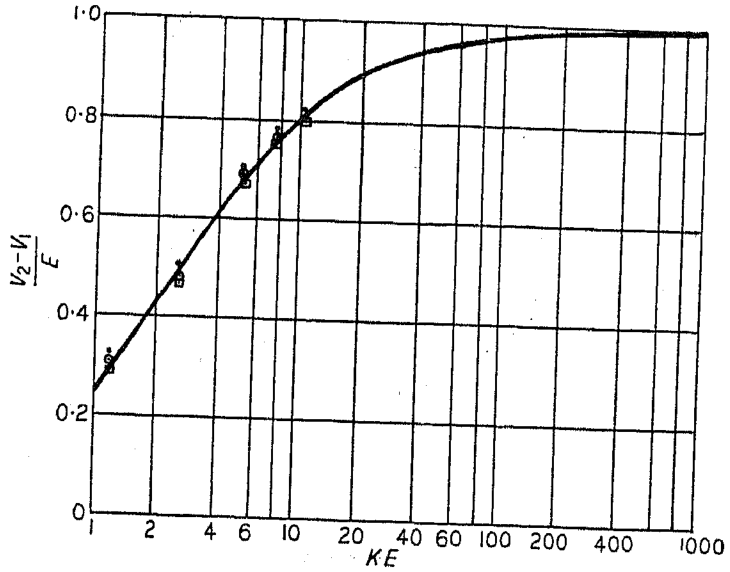

Fig. 14.—Ratio of apparent peak voltage ($V_2 - V_1$) to direct peak voltage E, as a function of KE.

● $I_a = 0{\cdot}5\ \mu$A.
○ $I_a = 1{\cdot}0\ \mu$A.
□ $I_a = 5{\cdot}0\ \mu$A.

If a sinusoidal voltage $E \cos \omega t$ is applied to the grid, the anode current will be given by

$$I_a = N\epsilon^{K(V_g + E \cos \omega t)}$$

It can be shown* that, if V_1 is the grid bias necessary to give a definite anode current with no alternating voltage applied to the grid, and V_2 the bias to give the same current when an alternating voltage of amplitude E is applied, then

$$\frac{V_2 - V_1}{E} = \frac{1}{KE} \log_\epsilon \mathbf{I}_0(KE) = f(KE)$$

where $\mathbf{I}_0$ is the zero-order modified Bessel function of the first kind.

For any value of E, $f(KE)$ can be calculated if K is known, so that the ratio $(V_2 - V_1)/E$ can be determined. The calculated value of the ratio $(V_2 - V_1)/E$ is plotted against KE in Fig. 14. It will be seen that, for values of KE above 100, the error involved in assuming $V_2 - V_1 = E$ is less than 3 %, but for small values of KE the error is very considerable. For example, if

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* See Bibliography, (5).

* See Bibliography, (6).

$K = 10$ and $E = 0 \cdot 2$ volt, the error involved in assuming $V_2 - V_1 = E$ is more than 50 %.

The theory shows that as long as the characteristic is exponential, the value of the anode current is immaterial, and this is borne out approximately in practice. The various points in Fig. 14 are experimentally determined, using an H63 triode with $V_a = 30$ volts, and show the ratio $(V_2 - V_1)/E$ against KE for $I_a = 0 \cdot 5\,\mu$A, $1 \cdot 0\,\mu$A, and $5 \cdot 0\,\mu$A. The points do not exactly coincide, presumably owing to the value of K being slightly higher at the lower anode currents.

If the value of K for the valve is known, the calibration can be calculated for the slide-back voltmeter and the instrument can then be used for the measurement of peak voltages down to about $0 \cdot 2$ volt with a fair accuracy. The calculated calibration is only accurate for sinusoidal voltages, and the ratio $(V_2 - V_1)/E$ for a non-sinusoidal voltage would depend on the wave-form.

The points marked " A " on the curves of Fig. 3 show the value of the grid bias and anode current for $0 \cdot 1\,\mu$A grid current. For the same grid current, the anode current is much larger with $V_a = 30$ volts than with $V_a = 15$ volts, so that, although the value of K is slightly smaller for $V_a = 30$ volts, the grid current is lower and therefore the input resistance is higher.

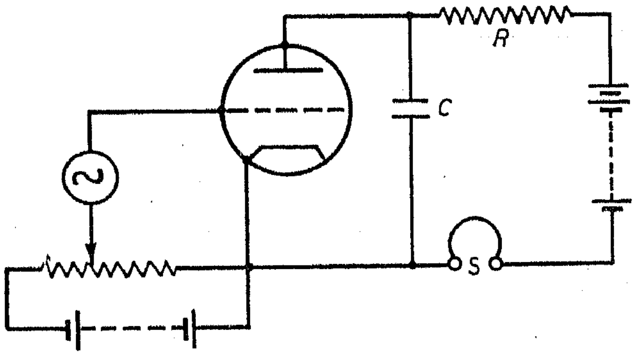

Fig. 15.—Gas-filled relay as slide-back voltmeter.

(ii) "Slide-back" type using gas-filled triodes.

The introduction of a gas such as mercury or argon into a triode valve makes it very suitable for use as a slide-back voltmeter. Such a valve passes no anode current if the grid potential is more negative than a certain value, while at a smaller value of grid potential gas discharge takes place and the current increases rapidly. This critical value of grid potential depends on the anode voltage and is very sharply defined.

In order to measure the peak value of an alternating voltage the grid bias is adjusted to its critical value and the a.c. voltage superimposed on the grid. The bias is again adjusted to its critical value and the difference in the two d.c. readings gives the peak value of the alternating voltage. The critical grid voltage can be adjusted by observing when the discharge takes place in the valve or by observing the current in a meter in the anode circuit. Both of these methods suffer from the disadvantage that the anode voltage has to be switched off, once the arc has been formed, as the grid has then no controlling action on the anode current. This disadvantage can be overcome by the use of a resistance-capacitance combination in the anode circuit of the valve, so that the anode voltage falls periodically to zero.* The circuit is shown in Fig. 15. The condenser C is charged by the battery through a resistor R, and when it attains a sufficient potential it discharges through the valve, producing a click in the phone S. The critical bias is indicated by a slow clicking in the phone; on one side there is silence, while on the other the clicking merges rapidly into a buzzing sound. The critical potential, with and without the alternating voltage, can therefore be determined accurately without any need of switching-off the anode voltage. Using a G.T.1.C. gas-filled relay, the difference in the bias voltages was found to be equal to the peak value of the alternating voltage to an accuracy of about 3 % down to $0 \cdot 5$ volt, the accuracy increasing as the peak voltage increased: the error for the same peak voltage using a hard triode is about 35 %. The disadvantages of using a gas-filled triode are: (i) the highest potential that can be measured is limited by the potential at which cold discharge takes place between grid and cathode; (ii) the critical grid voltage depends on the temperature of the gas—an argon-filled valve is therefore preferable to a mercury-filled valve; (iii) the ionization time is about 10 microseconds, while the deionization time may vary between 10 and 1 000 microseconds, according to the design, temperature, and operating conditions; (iv) when the negative grid bias is greater than the critical potential, the grid current is negligible, but at the critical point it can become quite appreciable. The instrument will therefore absorb power from the source, and in this respect is inferior to the hard valve.

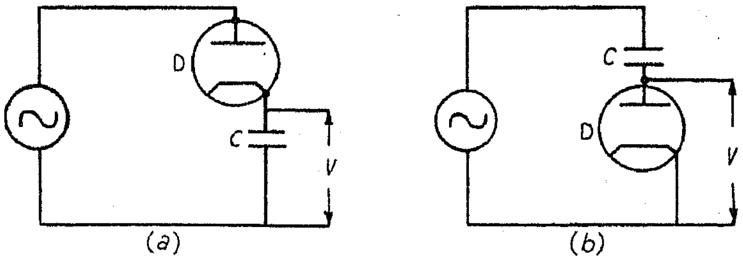

Fig. 16.—Diode peak voltmeter.

(b) Peak Voltmeters using Diodes.

One of the most convenient methods of measuring peak voltage, especially at very high frequencies, is to charge a condenser through a diode as in (*a*) and (*b*), Fig. 16. When equilibrium is reached, the d.c. voltage V is, in the ideal case, equal to the peak value of the alternating voltage. In practice, V is approximately equal to the peak value for voltages above 10 volts, but for lower voltages, errors occur due to the initial velocity of the electrons.

For very small currents, the anode-current/anode-voltage characteristic of a diode is exponential, so that if no other conducting path existed between cathode and anode the condenser would eventually charge up to an infinite potential. However, there is always a finite resistance across both valve and condenser, so that the condenser voltage reaches a steady value at which the initial velocity current is balanced by the leakage current.

If the effective resistance across the valve and condenser is R, and I_1 is the direct current through the resistance with no alternating voltage applied, then the condenser voltage V will be $-RI_1$.

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* See Bibliography, (7).

The electron current through the valve is given by

$$I_1 = I_s\epsilon^{KV}$$

Hence $$I_s\epsilon^{KV} = -\frac{V}{R}$$

If an alternating voltage $E\cos\omega t$ is now applied to the system, the direct current through the resistance will increase to I_2, and the voltage across the diode will be given by

$$V_a = E\cos\omega t - RI_2$$

The anode current will therefore be given by

$$I_a = I_s\epsilon^{KE\cos\omega t}\epsilon^{-KRI_2}$$

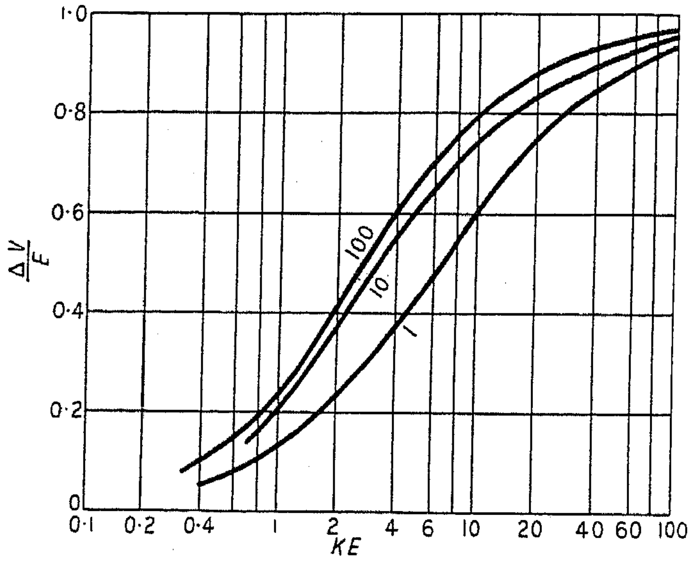

Fig. 17.—Efficiency of rectification as a function of KE.
$b = KRI_1$, where I_1 is the "no signal" diode current.
Numbers on curves give values of b.

This equation has been treated by Colebrook* and lately by Aiken.† Reference to these papers shows that the quantity $\epsilon^{KE\cos\omega t}$ can be expressed in the form

$$\epsilon^{KE\cos\omega t} = \mathbf{I}_0(KE) + 2\sum_{n=1}^{n=\infty}\mathbf{I}_n(KE)\cos n\omega t$$

Therefore the steady part of the current is

$$I_2 = I_s\mathbf{I}_0(KE)\epsilon^{-KRI_2}$$

The rectified voltage is equal to the change in the voltage-drop across the resistance R when the voltage E is applied. If this change is ΔV, then

$$\Delta V = R(I_2 - I_1) = RI_1\left[\mathbf{I}_0(KE)\epsilon^{-K\Delta V} - 1\right]$$

or $$\epsilon^{K\Delta V}(K\Delta V + b) = b\mathbf{I}_0(KE)$$

where $b = KRI_1$. That is, the rectified voltage is given in terms of the resistance R, the "no signal" current I_1, the constant K, and the input voltage E.

When R is fixed, I_1 is a constant, so that ΔV can be calculated for any value of E. Aiken shows curves connecting $\Delta V/E$ with KE for various values of b, and for the sake of clearness these curves are reproduced in Fig. 17.

The rectification efficiency $\Delta V/E$ increases both with K and with b, but it is shown that very little improvement is obtained if b is increased beyond 100. With a normal diode, the resistance R is generally of the order of 1 000 megohms, and b would lie between 10 and 20. With this value of R, and $K = 10$, $\Delta V/E$ would be equal to 0·95 for a peak voltage of 10 volts, the error decreasing as the peak voltage is increased. At $E = 100$ volts the error would be negligible.

It is important that the capacitance C should be large in comparison with the diode capacitance, so that all the alternating voltage appears across the diode. However, C should not be made unnecessarily large, because of the necessity of keeping the charging current down to a negligible figure, so that a diode with small electron emission, of long life and small dimensions, can be used.

If the transit time of the electrons between cathode and anode is comparable with the period of the applied voltage, some electrons will fail to reach the anode before the electric field in the diode reverses. The voltmeter will therefore read low at very high frequencies, and it has been shown* that the error is approximately proportional to the frequency (f) and to the cathode-to-anode distance (d), and inversely proportional to the square root of the applied voltage (E). For this error to be less than 1%, the ratio $fd/\sqrt{E}$ must be less than 0·1 when f is in megacycles per sec., d in centimetres, and E in volts.

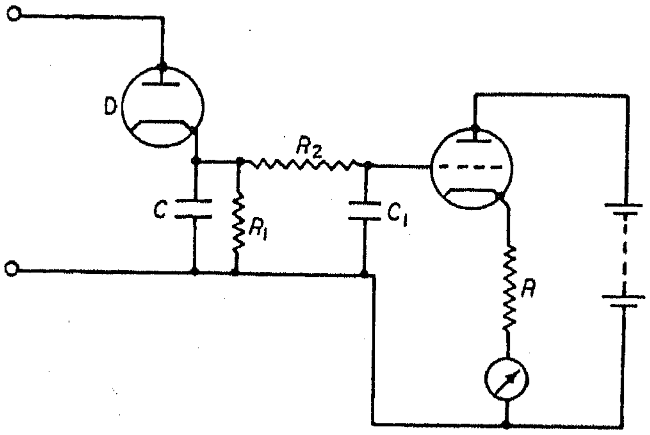

Fig. 18.—Schematic circuit diagram of degenerative d.c. amplifier for measuring the condenser voltage.

The voltage across the condenser can be measured conveniently by means of an electrostatic voltmeter, and the method has the advantage that the resistance can be kept very high. It has the disadvantage, however, that the reading of the voltmeter does not follow variations in the voltage to be measured. A resistance of the order of 10 to 50 megohms is therefore often connected across the condenser, but this resistance must be kept large so that the condenser voltage does not drop appreciably during a cycle of the applied voltage.†

An alternative and convenient method of measuring the condenser voltage is shown in Fig. 18.‡ The d.c. rectified voltage is applied to the grid of a triode valve, which has a high resistance R in series with the cathode. The condenser C_1 and resistor R_2 serve as a filter for the high-frequency voltage, while the resistor R gives rise to negative feedback in the triode. Then the change in anode current δI_a for a change δV_g in grid voltage is given by

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* See Bibliography, (8).

† *Ibid.*, (9).

* See Bibliography, (3) and (4).

Ibid., (10).

‡ *Ibid.*, (11).

$$\delta I_a = \frac{\mu}{r_a + R(1+\mu)}\delta V_g$$

where μ = amplification factor and r_a = anode a.c. resistance of the valve. If $R(1+\mu)$ is large in comparison with r_a, and $\mu >> 1$ (for a valve such as the Type H63, $\mu = 100$),

$$\frac{\delta I_a}{\delta V_g} \simeq \frac{1}{R}$$

That is, the change in anode current is approximately proportional to the change in grid voltage, while the sensitivity can be changed by altering the value of R. As the sensitivity is determined only by the resistance R, large variations in the valve characteristics and supply voltages will not affect appreciably the calibration of the instrument.

Fig. 19* shows a diode peak voltmeter in which the voltage is measured with an electrostatic voltmeter. The diode is housed in a brass head-piece supported by a flexible metal tube. This arrangement enables the valve to be brought very close to the point at which the voltage is being measured. The diode used has small input capacitance (0·4 $\mu\mu$F), small distance between anode and cathode, and short leads, so that the accuracy of measurement is about 3 % at 100 Mc./sec.; while the instrument can be used for approximate measurements up to 1 000 Mc./sec.

The smallest voltage that can be measured is determined by the range of the electrostatic instrument and its scale law. Greater sensitivity may be obtained by applying an additional direct voltage in series with the electrostatic voltmeter so that it records over a more open part of the scale. In the case where a triode is used for measuring the direct voltage, full-scale deflection on a 200-microamp. instrument can be obtained for 1 volt input by a suitable choice of the cathode resistance.

(c) Grid-leak Voltmeters

The circuit of the simplest form of grid-leak voltmeter is shown in Fig. 20. With no alternating voltage applied to the grid, current will flow through the resistor R, thus biasing the valve negatively; the bias depending on the value of the resistance. When an alternating voltage is superimposed, rectification takes place in the grid circuit; the current through the resistor increases, and therefore the mean bias increases.† The operation is the same as that of the diode voltmeter: the grid behaves as the anode of the diode, and the change in anode current is taken as a measure of the change in the grid bias.

For values of grid current less than 1 microamp., the grid-current/grid-voltage characteristic of a triode such as the Type H63 is exponential. Hence the change in grid bias can be calculated in exactly the same way as the change in anode potential for the diode, i.e. the change ΔV in the d.c. potential of the grid is given by

$$\epsilon^{K\Delta V}(K\Delta V + b) = b\mathbf{I}_0(KE)$$

If the anode-current/grid-voltage characteristic is linear, then this change in mean grid voltage ΔV will give rise to a change in anode current, $\Delta I_a = g_m \Delta V$, where g_m is the mutual conductance. Normally the anode current is only linear over a limited range of grid voltage, so that if the input voltage is large " anode bend " rectification will take place as well. The anode current is decreased by grid-leak rectification and increased by anode-bend rectification, so that if the latter takes place the sensitivity is reduced. Since both types of rectification are generally present, it is difficult to calculate the voltmeter response, and it is usual to calibrate the instrument experimentally.

(d) Anode-bend Voltmeters

The anode-bend voltmeter uses the curvature of the anode-current/grid-voltage characteristic of a valve for rectification, and the theory is so well known that only a brief reference to it is needed.

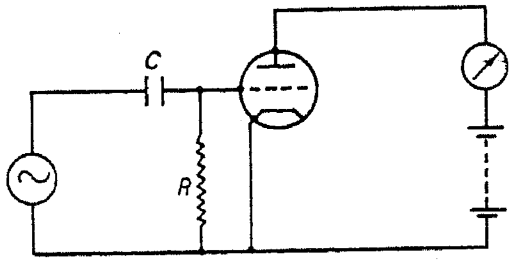

Fig. 20.—Simple grid-leak voltmeter.

(i) Square-law type.

The anode current of a triode valve can be expressed in the form

$$I_a = f(V_a + \mu V_g)$$

where V_a and V_g are the anode and grid voltages respectively. When there is no load in the anode circuit, V_a is constant, so that

$$I_a = f(V_g) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

For triodes with a low μ value this function is a parabola for a considerable range of grid voltage,* so that (2) may be written

$$I_a = a_1 + a_2 V_g + a_3 V_g^2$$

where a_1, a_2, a_3 are constants.

If a voltage $v = E\cos\omega t$ is impressed on the grid, then the change i in the anode current, as read on a d.c. meter, will be given by

$$i = \frac{E^2}{4}\frac{\partial^2 I_a}{\partial V_g^2} = \frac{E^2}{2}a_3$$

The rectified current is therefore proportional to the square of the input voltage, and the d.c. meter can be calibrated to read the r.m.s. value of the voltage: this calibration will hold whatever the wave-form of the input.

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* Fig. 19 was shown as a lantern slide at the meeting.
† See Bibliography, (12).

* See Section (2).

If higher even differential coefficients are present, the calibration will not be square-law, and if the instrument is calibrated with a sinusoidal voltage it will not read correct r.m.s. values with a distorted input.

(ii) Linear type.

It is sometimes convenient to have a more linear relationship between the change in anode current and the input voltage. This may be obtained by connecting a high resistance in the anode circuit of the valve. As the anode current increases, the mean anode potential falls, so that the rate of increase of mean anode current is lessened.*

The maximum alternating voltage which can be impressed on the grid, before the input resistance falls on account of the rise of grid current, is limited by the value of the grid bias. If, however, the high resistance is included in the cathode lead, the voltage drop across this resistance not only lowers the anode potential but also acts as an additional negative bias.† As the alternating voltage on the grid is increased, the anode current and negative grid bias increase and much larger voltages can therefore be applied to the grid before grid current flows. The voltmeter can also be designed to have several voltage-ranges by changing the value of the resistance according to the range required. The resistance also improves the stability of the instrument with regard to changes in valve characteristics and electrode voltages.

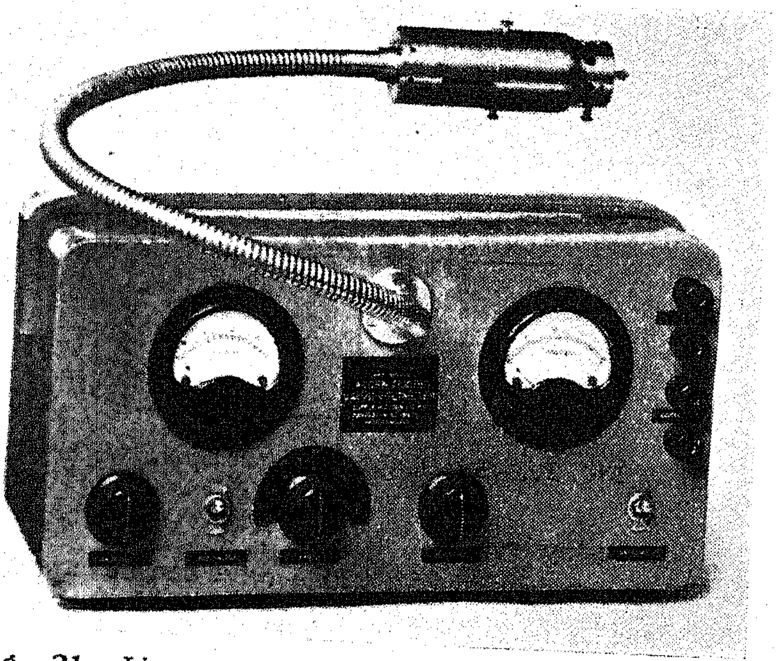

Fig. 21.—Linear-type voltmeter employing an "acorn" valve. The valve is housed in the metal head-piece at the end of the flexible metal tube.

A voltmeter designed in this way would read r.m.s. values with small input voltages, but would approximate to a peak voltmeter with large input voltages. A considerable error would therefore be introduced if the voltmeter were calibrated with r.m.s. voltages and used to measure large values of a distorted voltage.

The sensitivity of all rectifier-type voltmeters can be increased considerably if the "no signal" anode current is balanced out and a more sensitive current meter used. This can be done conveniently by means of a resistance-bridge circuit. A limit of sensitivity is reached when variations in the valve H.T. and L.T. voltages give rise to variations in the zero reading, but these variations can be overcome to a large extent if another similar valve is placed in one arm of the bridge. If the voltages then change, the currents in the rectifying and balancing valves will change by similar amounts and the zero stability of the instrument will be greatly improved.

Fig. 21 shows a voltmeter of the linear type employing an "acorn" valve. As in the case of the diode voltmeter, the valve is mounted in a metal head-piece supported by a flexible metal tube. The "acorn" pentode valve is used in this instrument, because the arrangement of the valve leads enables more efficient by-passing condensers to be used than in the case of the triode. The input capacitance of the instrument is 3·5 $\mu\mu$F and owing to the short electron transit-time in the valve the voltmeter is suitable for use at very high frequencies, the input impedance at 50 Mc./sec. being as high as 100 000 ohms.

Another type of linear voltmeter, employing a negative-feedback amplifier, is described by J. Greig and H. N. Wroe.* It is claimed that mean values of distorted low-frequency voltages of small amplitude can be accurately determined by this means.

(iii) Logarithmic type.

In cases where it is required to measure a large range of voltages, a voltmeter whose indications are proportional to the logarithm of the input voltage is a decided convenience. This is particularly true in regard to the recording of radio field-strengths or the measuring of the frequency response of amplifiers and loud-speakers. Several arrangements for logarithmic indication have been devised, in which the curvature of the anode-current/grid-voltage characteristics of variable-mu tetrode or pentode valves have been used for varying the amplification.

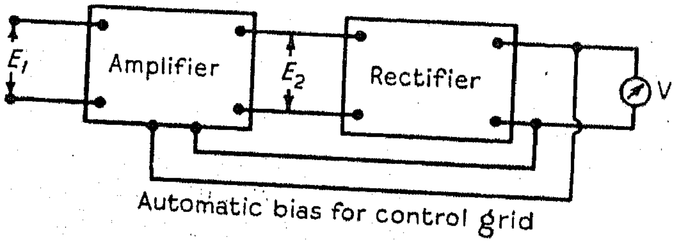

Fig. 22.—Schematic diagram of logarithmic voltmeter.

One such arrangement† is illustrated schematically in Fig. 22. The amplifier consists of one or more exponential valves, the number chosen depending on the range of input voltage (E_1) to be measured. The amplification is controlled by an automatic grid bias, derived from the rectifier connected to the output terminals, and when the circuits are properly designed the output voltage E_2 will be nearly constant over the range of input voltages to be measured. If the value of the automatic grid bias is indicated by a voltmeter, the deflection of the latter is approximately proportional to the logarithm of the input voltage.

It is possible‡ to design the grid of the valve in such a way that the anode-current/grid-voltage characteristic is given by $I_a = N\epsilon^{bV_g}$ and therefore $g_m = Nb\epsilon^{bV_g}$. If V is the automatic grid bias, the gain of the amplifier will be given by $E_2/E_1 = C\epsilon^{nbV}$, where C is a constant and n is the number of amplifier valves.

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* See Bibliography, (12).

† *Ibid.*, (13) and (14).

* See Bibliography, (49).

† *Ibid.*, (15).

‡ See Section (2).

Hence
$$V = \frac{1}{nb}\log_\epsilon \frac{E_1 C}{E_2}$$
or
$$V + \frac{1}{nb}\log_\epsilon \frac{E_2}{C} = \frac{1}{nb}\log_\epsilon E_1$$

Above a certain critical value, E_2 will be approximately constant, so that the automatic grid bias V will be approximately proportional to $\log E_1$.

Other arrangements have been described by F. V. Hunt* and J. B. Rudd.†

(4) THE MEASUREMENT OF D.C. VOLTAGE

As in the case of a.c. measurements, the principal advantage of the valve voltmeter for direct current lies in the extremely small amount of power absorbed from the source. It is, however, only in rather exceptional circumstances, when the combination of very high input-resistance and high sensitivity is required, that d.c. valve voltmeters are used in preference to moving-coil or electrostatic instruments.

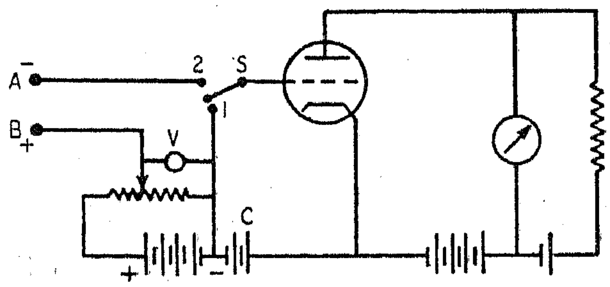

Fig. 23.—Valve voltmeter for measuring d.c. voltage.

In the simplest form of d.c. valve voltmeter the voltage to be measured is superimposed on a fixed negative bias applied to the grid of a triode and the change in anode current measured, the valve having first been calibrated from a known voltage source. Increased sensitivity and a linear scale can be obtained by balancing out part of the anode current and operating the valve over the linear portion of the I_a/E_g characteristic, the limit of sensitivity being determined by the anode-current meter and by variations in valve characteristics and supply voltages.

A more usual method is, however, to apply the unknown voltage to the grid of a triode in opposition to a known voltage from a potentiometer, as shown in Fig. 23. With the switch S in Position 1, a fixed negative bias of a few volts is applied to the grid to prevent grid current from flowing, and the anode current is noted (or, for greater sensitivity, the resistance bridge in the anode circuit adjusted to give an arbitrary scale-reading on the galvanometer). The voltage to be measured is applied to the input terminals AB and the potentiometer adjusted until no change occurs on switching from Position 1 to Position 2. The accuracy of the instrument is independent of changes in valve characteristics or supply voltages (provided these changes are not too sudden), and voltages as low as 0·1 mV can be measured with quite a robust galvanometer in the anode circuit provided sufficient care is taken in designing the switch S. If ordinary receiving valves are used, the input resistance of the voltmeter will be at least 10^8 ohms.

For some purposes, e.g. the measurement of glass-electrode potentials in the determination of hydrogen-ion concentration, considerably higher input resistance and greater stability are, however, necessary, and here two methods are available.

The first makes use of an ordinary triode with the grid operated at its "floating" potential, i.e. the potential (usually about 1 volt negative with respect to the cathode) which the grid will acquire when left free. When the valve is in this condition the various components of grid current mentioned in Section (2) (*b*) exactly balance one another, as indicated by the point P in Fig. 9, and the grid-cathode circuit imposes zero load on an external circuit to which it may be connected. If, therefore, the voltage of the bias battery C shown in Fig. 23 is chosen to equal the floating grid potential, the input resistance of the valve voltmeter is infinite. The actual value of the floating grid potential depends, however, on the contact potential-difference between grid and cathode, the residual gas pressure in the valve, inter-electrode leakage, and the values of anode current and anode voltage. Fluctuations in the first three of these parameters are to a large extent avoided by ageing the valve for a long period, but rather elaborate circuits are necessary in order to compensate for anode-current and supply-voltage variations. The theories of such circuits have been discussed fully elsewhere,* and a summary of the various methods, their relative advantages, and their limitations, has been given by Nottingham.† Probably the most satisfactory circuit is that in which two valves are employed which, with their anode resistances, are arranged to form a resistance bridge. Fig. 24 shows the circuit of an instrument of this type which has been described by McFarlane.‡ The grid of the valve to which the input is applied is adjusted to its floating potential, and by means of adjustments to the positions of the contacts P, Q, and R a condition can be reached at which quite large variations in the supply voltage and

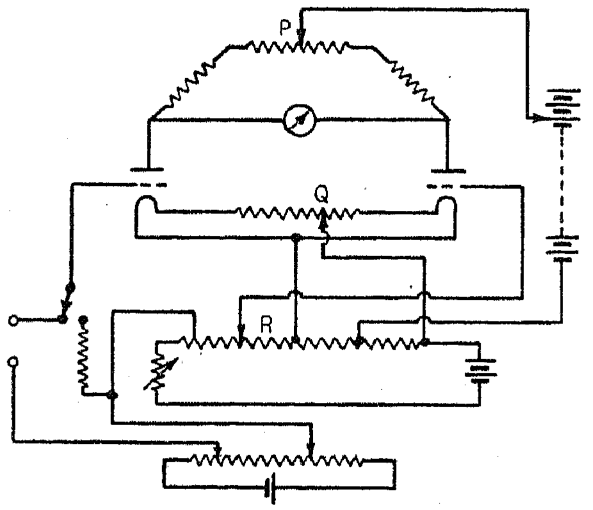

Fig. 24.—Valve voltmeter for d.c. voltages, described by McFarlane.

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* See Bibliography, (16).

† *Ibid.*, (17).

* See Bibliography, (18), (19), (20), (21), and (22).

† *Ibid.*, (23).

‡ *Ibid.*, (24).

in the valve characteristics do not upset the zero of the instrument. A sensitivity of 0·1 mV is claimed and, provided the grid a.c. resistance ($\partial E_g/\partial I_g$) at the floating potential is greater than 10^9 ohms, a condition satisfied in most valves, slight fluctuations in the actual value of this potential will not seriously upset the input resistance.

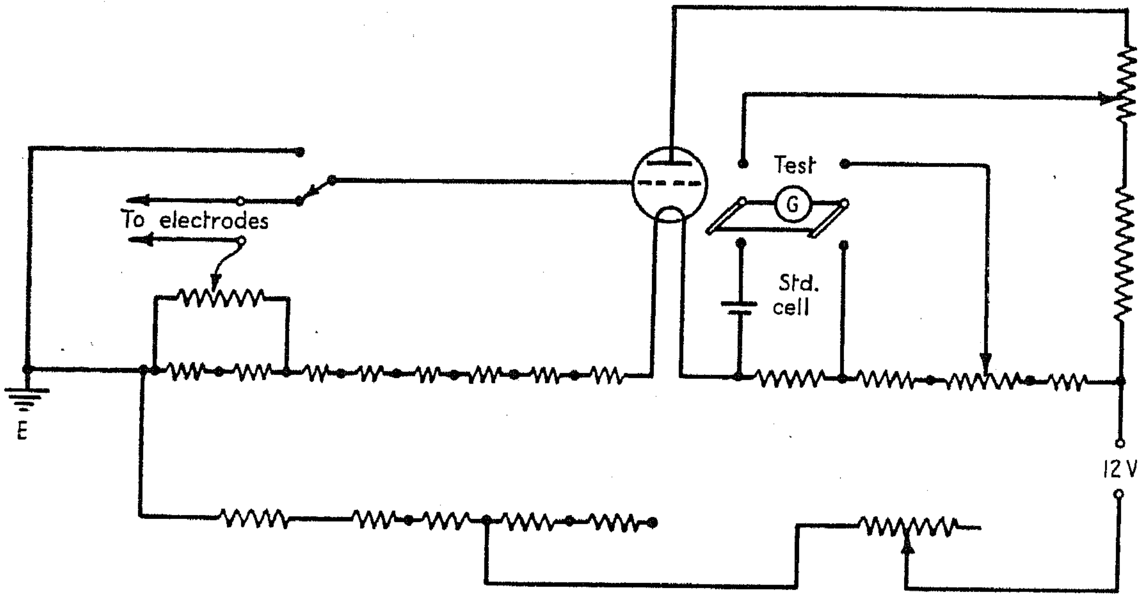

Fig. 25.—Valve electrometer described by Morton.

The second method, first described by Harrison,* makes use of a valve of the electrometer type mentioned earlier in this paper (see Fig. 10) in which the grid current is extremely low at *any* negative potential greater than about 2 volts (Fig. 11). Valves of this type are designed to operate at low anode potentials, and Morton† has described a portable instrument using the Type E.T.1 valve with a self-contained potentiometer, standard cell, and robust galvanometer. The potentiometer current, grid bias, filament current, anode voltage, and compensating current are derived from a common source and are standardized in one operation. The input resistance is about 10^{15} ohms, and the instrument is self-adjusting for fluctuations in battery voltage (Fig. 25).

Compton and Haring‡ have described a compensated thermionic electrometer in which use is made of the electrometer tetrode Type FP54. Compensation for fluctuations in battery voltages is here effected by balancing the current-changes in the anode and the space-charge grid circuits, and it is claimed that the instrument compares favourably with bridge circuits both as regards stability and sensitivity.

A d.c. voltmeter has recently been described by Smith and Sullivan§ in which use is made of a type of tuning indicator frequently employed in radio receivers. This consists of a combination of a triode valve and a sector-shaped cathode-ray beam which falls on a fluorescent screen, the angle of the beam and therefore the fluorescing area of the screen being controlled by an auxiliary electrode connected to the anode of the triode. Fig. 26 shows the relation between the angle of the non-fluorescing sector of the screen and the voltage applied to the grid of the triode component for a valve of this type (Y63) under normal operating conditions. Although high accuracy cannot be claimed for this type of instrument, it possesses the advantages of robustness and portability (there are no delicate moving parts), and, furthermore, the electron beam—having negligible inertia—follows instantaneously rapid changes in the voltage applied to the triode.

In the measurement of small d.c. voltages, whether by valves operating at the floating grid potential or by electrometer valves, very complete screening is necessary in order to avoid stray alternating currents being picked up in the input circuit and rectified by the valve, and also to prevent charges from accumulating on the bulb of the valve, which would disturb the characteristics. In many cases it is recommended that the valve should be operated in the dark to prevent the emission of photo-electrons from the grid.

(5) THE MEASUREMENT OF CURRENT

In normal instrument practice, current is measured either by its magnetic or by its heating effect, and voltage is determined by measuring the current through a known resistance. In the case of instruments employing valves the converse procedure is adopted. Voltage is measured by its controlling action on the electron current in the valve, while current may be determined

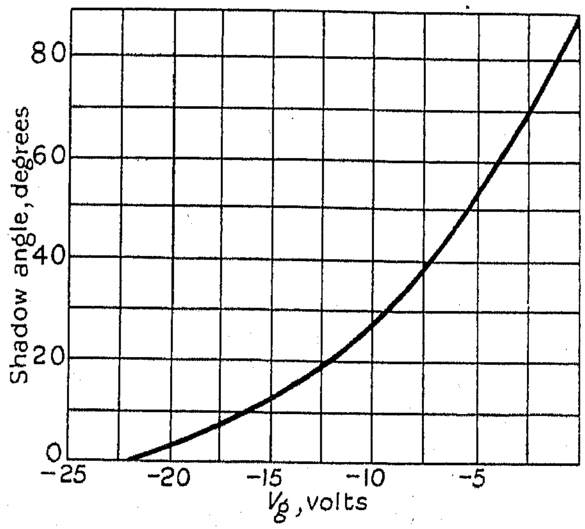

Fig. 26.—Variation of shadow angle with grid voltage for Y63 valve.

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* See Bibliography, (25).

† *Ibid.*, (26).

‡ *Ibid.*, (27).

§ *Ibid.*, (28).

by measuring the voltage produced across a known resistance. This method is particularly suitable for the measurement of extremely small currents, either alternating or direct, which can be passed through a fairly high resistance, and any of the valve voltmeters mentioned above may be used in this way. Du Bridge* has described several circuits using the electrometer tetrode Type FP54 and has found it possible to measure direct current of the order of 10^{-16} amp. by this means. Soller† and Moles‡ have also described methods of obtaining comparable sensitivity, while Teegan and Hayes§ have used the electrometer triode Type E.T.1 for the measurement of small ionization currents of similar magnitude. Winch and Harper‖ have employed the electrometer triode to measure small photo-electric currents and have designed an instrument for photometric measurements in which the electrometer and photocell together with a grid resistance of 50 megohms are sealed into an evacuated glass bulb to prevent leakage currents due to moisture on the outside surface of the valve (Fig. 27).

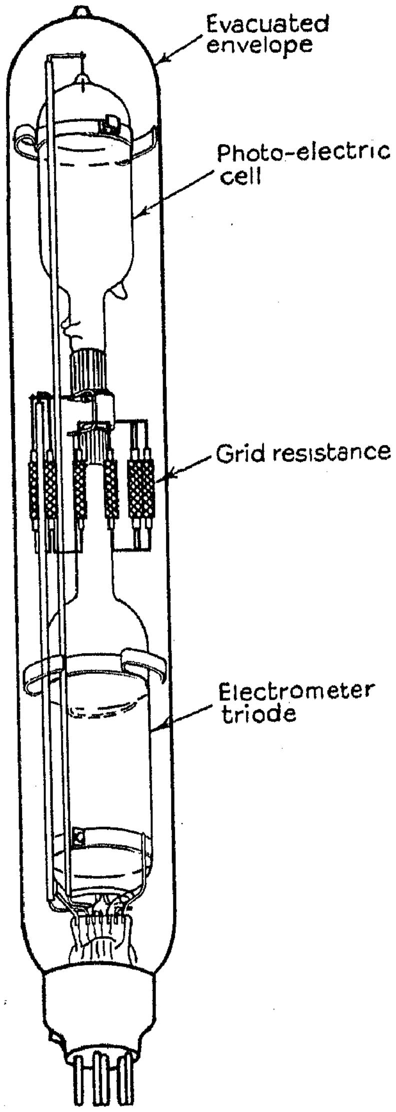

Fig. 27.—Electrometer-photocell unit.

For greater sensitivity, additional stages of valve amplification may be used, but with such amplifiers, particularly in d.c. measurements, variations in valve characteristics and voltages are troublesome. If, however, negative feedback is applied to the amplifier, the effect of variation of electrode voltages on the gain can be reduced to negligible proportions.

It has been shown* that the gain m_1 of an amplifier in which a fraction β of the output is fed back in series with the input is given by

$$m_1 = \frac{m}{1 + m\beta}$$

If $\beta = 1$, i.e. if all the output is connected in series with the input,

$$m_1 = \frac{m}{1 + m} = 1 - \frac{1}{1 + m}$$

If the gain, m, of the amplifier without feedback is large, $m_1 \simeq 1$, and the output voltage is equal to the input voltage, being independent of variations in the supply voltages to the amplifier valves.

If R_1 is the input resistance to the amplifier, R_2 the output resistance, I_1 the input current, and I_2 the output current,

Then $$R_1 I_1 = R_2 I_2$$

and $$I_1 = \frac{R_2}{R_1} I_2$$

If a current meter is connected in series with R_2 or a voltmeter connected across R_2, the instrument becomes a voltmeter whose resistance is determined solely by the resistance R_1. By using a wide range of input resistances the instrument becomes an ammeter with a corresponding wide range. Since the power supplied to the output meter is supplied by the H.T. voltage through the output valve, a rugged and accurate meter of low sensitivity may be used, while great sensitivity may be obtained by the use of high input resistances.

A. W. Vance† describes such an instrument in which a 0·1-volt voltmeter is used as the output meter. Hence with an input resistance of 10^7 ohms, full-scale deflection is obtained with a current of 10^{-8} amp., while with 100 ohms input resistance a current of 1 milliamp. would give full-scale deflection. The amplifier output can be so designed that the maximum output obtainable is insufficient to damage the output voltmeter, so that the instrument can stand very large overloads.

Another method of current measurement depends for its action on the use of a diode valve, operated under saturation conditions. When the filament of a thermionic diode is heated to an absolute temperature τ, the saturation current is given by

$$I_s = A\tau^2\epsilon^{-b/\tau}$$

where A and b are constants.

The filament can be heated by either direct current or alternating current, while the saturation current can be measured with a d.c. instrument. The valve therefore enables one to measure an alternating current in terms of a direct current.

One instrument employing the above principle is described by Barlow.‡ The filament of a diode is heated in the first place by a direct current to a temperature somewhat below the normal working temperature, and the H.T. voltage applied is sufficiently positive to saturate the anode current. The valve is arranged as one arm of a resistance-bridge network, a moving-coil galvanometer indicating when the bridge is balanced (Fig. 28). The alternating current is superposed on the direct current through the filament of the valve, thereby increasing the temperature and anode current and upsetting the balance of the bridge. The reading of the galvanometer is calibrated to read directly the value of the alternating current. The balance of the bridge depends critically on the direct current through the filament, so that any variation in the filament-battery voltage will cause a troublesome drift in the zero of the instrument. To overcome this difficulty one arm of the bridge can be replaced by another similar diode, the two filaments being run in series; the stability is then greatly improved and the sensitivity increased.

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* See Bibliography, (29).
† *Ibid.*, (30).
‡ *Ibid.*, (31).
§ *Ibid.*, (32).
‖ *Ibid.*, (33).

* See Section (2).
† See Bibliography, (34).
‡ *Ibid.*, (35).

The instrument has the advantages that r.m.s. values are measured whatever the wave-form, the overload capacity is large, and different ranges can be provided by varying the series or shunt resistance of the galvanometer; but it has the disadvantage that it cannot be calibrated with direct current as in the case of vacuo thermo-junctions.

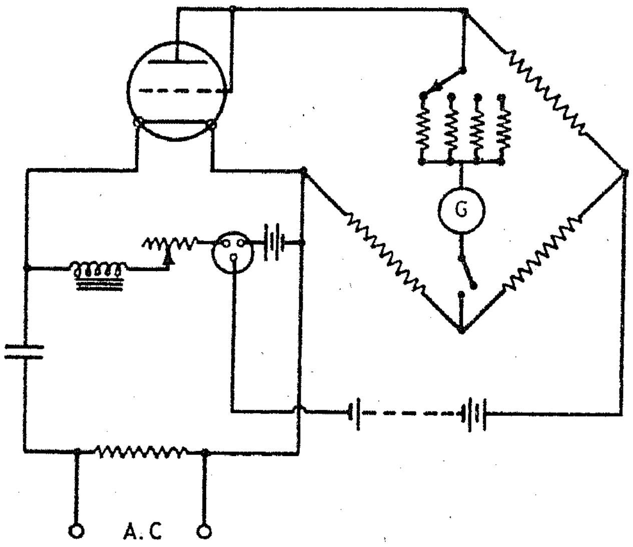

Fig. 28.—Circuit of valve ammeter described by Barlow.

The frequency range is determined by the design of the circuit for applying the alternating current to the instrument. Barlow shows that the instrument can be designed to have an accuracy better than 1 % for a frequency range between 25 and 5 × 10^6 cycles per sec.

Another instrument employing the same principle is described by Martyn.* Alternating current from a local oscillator supplies the main heating current of the filament, and the alternating current to be measured is superimposed on the current from the local oscillator. When the frequency of the oscillator is varied the anode current of the diode is constant at first; then the needle of the instrument begins to oscillate, the amplitude increasing until the two frequencies are the same. Synchronization then takes place, the two currents "locking" in phase or in antiphase, and the anode current reaches a pronounced maximum or minimum value. The value of the unknown alternating current is determined from the difference between the values of the anode current in the synchronized condition and in the condition when the frequencies differ so widely as to produce a constant reading. Although the method seems more complicated than that of Barlow, the sensitivity is such that an alternating current of 1 microamp. produces a change in the anode current (d.c.) of 0·5 microamp.

(6) VALVE WATTMETERS

The measurement of small amounts of power at radio frequency presents a difficult problem. Ordinary low-frequency wattmeters cannot be used because of their inductive and capacitive effects. The use of thermionic triodes, however, enables very small powers to be measured with a fair degree of accuracy.*

The circuit of such a wattmeter is shown in Fig. 29. R, R are equal non-inductive resistors and R_s a high-resistance potentiometer. The galvanometer G is arranged to measure the difference in the anode currents of the two triodes V_1 and V_2.

If v is the voltage across R_s, and i the current flowing through the resistors R, R (i is the load current), then the voltages applied to the grids of V_1 and V_2 respectively are

$$\left(\frac{r}{R_s}v + Ri\right) \quad \text{and} \quad \left(\frac{r}{R_s}v - Ri\right)$$

The anode-current/grid-voltage characteristic of a suitably designed triode is a parabola† over a considerable voltage range. That is,

$$I_a = a_1 + a_2V_g + a_3V_g^2$$

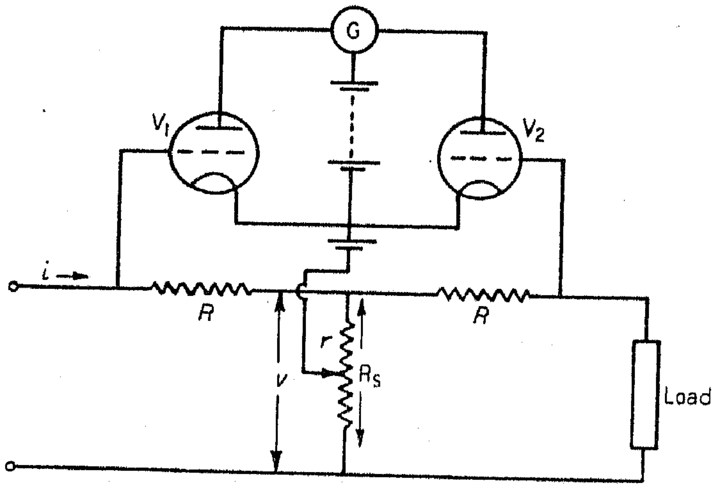

Fig. 29.—Valve wattmeter.

The anode currents of the two valves may therefore be written as

$$I_1 = a_1 + a_2\left(\frac{r}{R_s}v + Ri\right) + a_3\left(\frac{r}{R_s}v + Ri\right)^2$$

$$I_2 = a_1 + a_2\left(\frac{r}{R_s}v - Ri\right) + a_3\left(\frac{r}{R_s}v - Ri\right)^2$$

if the valves are identical. The difference, which is read on the galvanometer, is

$$I_1 - I_2 = 2a_2Ri + 4a_3\frac{Rr}{R_s}vi$$

If $\quad V = E\cos(\theta + \phi) \quad$ and $\quad i = I\cos\theta$

then $I_1 - I_2 = 2a_2RI\cos\theta + 4a_3\frac{Rr}{R_s}EI\cos\theta\cos(\theta + \phi)$

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* See Bibliography, (36).

* See Bibliography, (37) and (38).

† See Section (2).

The direct component of this expression (which is the only component read by the galvanometer) is

$$4a_3\frac{Rr}{R_s}EI\cos\phi$$

That is, the galvanometer deflection is proportional to the power ($EI\cos\phi$).

A small error is introduced by the power dissipated in the resistors R, but this is usually negligible, so that the instrument is direct-reading. A correction can, however, be made when the power to be measured is very small. By a substitution of the resistors, a range of powers from 1 milliwatt to an indefinitely large value can be measured with a fair degree of accuracy.[*]

Another type of valve wattmeter is described by J. R. Pierce[†] in which a multi-electrode valve of the hexode (or heptode) type is used. The disposition of the electrode system is shown in Fig. 30. In such a valve, G_2 and G_4 are at a fixed positive potential with respect to the cathode, while G_1 and G_3 are biased negatively. The current passing through G_1 will then be dependent only on the potential of G_1 and G_2, being independent of the potential of G_3, while the proportion of this current reaching the anode will depend only on the potential of G_3 and G_4. If the anode-current/grid-voltage characteristics of G_1 and G_3 are both linear, then the anode current will be represented by

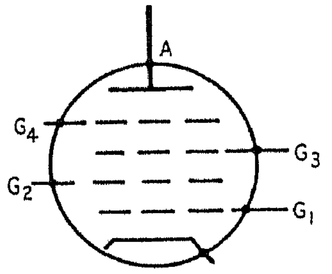

Fig. 30.—Disposition of the electrode system in a hexode valve.

$$I_a = A_1V_{g_1} + A_2V_{g_1}V_{g_3} + A_3V_{g_3} + A_4$$

If alternating voltages $E_1\cos\theta$ and $E_2\cos(\theta+\phi)$ are applied to the grids G_1 and G_3, the only d.c. component of I_a will be given by the second term in the above expression and will be equal to $A_2E_1E_2\cos\phi$, i.e. the change in reading of a d.c. instrument in the anode circuit is proportional to the power, if E_1 is made proportional to the voltage and E_2 to the current in the load. Existing multi-electrode valves have such a small range of linearity that an error is introduced due to anode-bend rectification, but if two valves in push-pull are used the error is considerably reduced: Pierce[‡] describes such an arrangement in which powers ranging from 10 milliwatts to 200 watts can be measured.

(7) HARMONIC ANALYSERS

Most harmonic analysers in which a valve is the essential part of the instrument depend for their operation on the parabolic anode-current/grid-voltage characteristic of the valve, namely

$$I_a = a_1 + a_2V_g + a_3V_g^2$$

If a sinusoidal voltage $E_0\cos\omega_0t$ and a voltage E of complex wave-form are applied in series to the grid of the valve, the anode current will be given by

$$I_a = a_1 + a_2(E_0\cos\omega_0t + E) + a_3(E_0\cos\omega_0t + E)^2$$

If $E = E_1\cos\omega_1t + E_2\cos\omega_2t + E_3\cos\omega_3t + \ldots$

then

$$\begin{aligned} I_a = a_1 &+ a_2(E_0\cos\omega_0t + E_1\cos\omega_1t + E_2\cos\omega_2t + \ldots) \\ &+ a_3(E_0\cos\omega_0t + E_1\cos\omega_1t + E_2\cos\omega_2t + \ldots)^2 \end{aligned}$$

This expression, when expanded, contains terms of frequency given by:—

$$\begin{aligned} &\omega_0, \omega_1, \omega_2, \\ &(\omega_0+\omega_1), (\omega_1+\omega_2) \\ &(\omega_0-\omega_1), (\omega_1-\omega_2), \ \ldots \text{ etc.} \end{aligned}$$

If, however, ω_0 is made almost equal to ω_1, the only very low-frequency component of I_a is $a_3E_0E_1\cos(\omega_0-\omega_1)t$. If now ω_0 is changed to be almost equal to ω_2, the only low-frequency component will be $a_3E_0E_2\cos(\omega_0-\omega_2)t$, and similarly for the ω_3, ω_4, etc., harmonics. That is, if the frequency of the local sinusoidal oscillation is adjusted to be very nearly equal to the frequency of the harmonic to be measured, the needle of the anode-current measuring instrument will oscillate slowly in response to the difference frequency.[*] The amplitude of swing of the needle will be

$I_1 = 2a_3E_0E_1$ for the fundamental,
$I_2 = 2a_3E_0E_2$ for the 2nd harmonic,
$I_3 = 2a_3E_0E_3$ for the 3rd harmonic,
etc.

The coefficient 2 takes into account the maximum positive and negative values of $\cos(\omega_0-\omega_1)t$, etc.

The peak amplitude of any harmonic is therefore given by

$$E_n = \frac{I_n}{2a_3E_0}$$

If E_0 is kept constant, the ratio of any harmonic to the fundamental is the ratio of I_n to I_1, while the absolute values can be determined if a_3 and E_0 are known.

If the output of the local oscillator contains harmonics, beat notes may be obtained between them and the harmonic which it is desired to measure. But if the local oscillator does not contain more than a few per cent of harmonics, the error can be shown to be negligible.

If the characteristic is not parabolic, a term $a_4V_g^3$ will appear in the equation, and it can be shown that the current amplitude due to the 2nd harmonic will then be

$$I_2 = 2a_3E_0E_2 + \frac{3a_4}{2}E_0E_1^2$$

Thus a term $\frac{3a_4}{2}E_0E_1^2$ is introduced, but it can be made negligible by making E_1 small. This, however, reduces the sensitivity of the instrument, which is undesirable. The difficulty can be overcome by using two valves in push-pull;[†] the anode-current changes due to the terms a_2V_g, $a_4V_g^3$, etc., then cancel out, and the error due to $a_4V_g^3$ is eliminated.

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[*] See Bibliography, (38).

[†] *Ibid.*, (39).

[‡] *Ibid.*, (39).

[*] See Bibliography, (40).

[†] *Ibid.*, (40).

If, however, a fourth-order term is present in the characteristic, a spurious third harmonic is produced in each valve, and these add together in the push-pull arrangement. The fourth-order term, however, is found to be very small in practice and may be neglected.

The order of accuracy that is obtainable with the instrument is better than 1 % for a harmonic of 10 % of the fundamental, and about 3 % for a 1 % harmonic.

If, instead of adjusting the frequency of the local oscillator to be approximately equal to that of the harmonic to be measured, one adjusts the frequency so that $(\omega_0 - \omega_1)$, etc., are always equal to ω', then the component of frequency $\omega'/(2\pi)$ can be amplified by a selective amplifier tuned to $\omega'/(2\pi)$, and the output read on a meter. This system has the advantages that the sensitivity is increased so that the input to the analyser can be kept small, thereby decreasing the error due to the unbalanced cube term. The output reading is then proportional to the amplitude of the harmonic, and it does not necessitate taking the difference of two readings as in the first method.

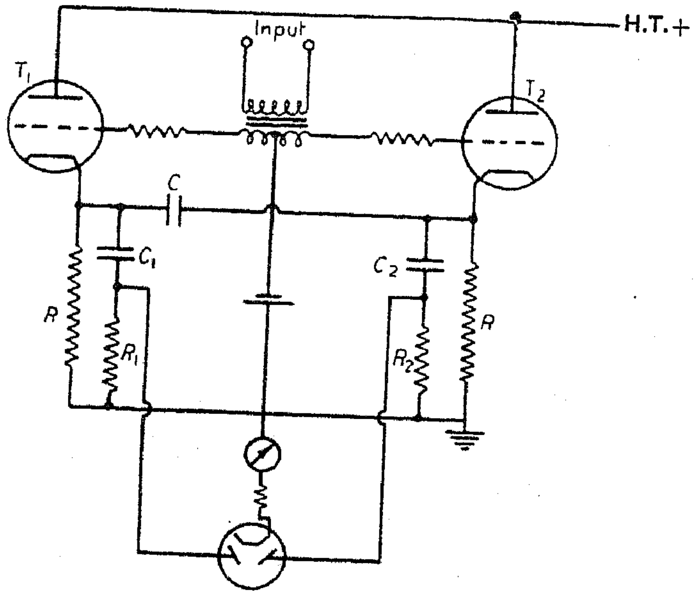

Fig. 31.—Direct-reading frequency meter.

(8) MEASUREMENT OF FREQUENCY

The common methods of measuring frequency are bridge methods and the use of calibrated tuned circuits, resonance being indicated by voltage or current. Neither of the methods is direct-reading, and therefore rapid changes of frequency cannot be measured.

A direct-reading audio-frequency meter is described by F. V. Hunt* in which rapid variations in frequency can be measured, and which is suitable for recording frequency as a function of time. The instrument employs two gas-filled triode valves in conjunction with a double-diode valve. The circuit is shown in Fig. 31.

The signal whose frequency it is desired to measure is applied to the grids of two gas-filled triode valves T_1 and T_2 in push-pull, so that when the grid of T_1 goes more positive the grid of T_2 goes more negative. If at any instant T_1 is carrying its normal discharge current, while T_2 is non-conducting, then the condensers C and C_1 become charged to a potential V_R, equal to the drop across the load resistance R in the cathode of T_1, while C_2 is uncharged. If now, the input signal varies so that the grid of T_2 becomes more positive, arc discharge will be initiated in T_2, and the potential of the cathode of T_2 will be raised abruptly to a value V_R. As the voltage across the condenser C cannot alter instantaneously, the cathode of T_1 will momentarily be made more positive with respect to its anode, and since its grid is at this instant negative, the arc in T_1 will be extinguished, provided the de-ionization time of the valve is not greater than the time required for C to discharge through R. Similarly the voltage of one anode of the double-diode valve will be raised momentarily and a current pulse will be delivered to the indicating instrument. When the input signal next varies in such a way that the grid of T_1 becomes more positive a similar sequence of events takes place.

Since the average current in the indicating instrument is proportional to the number of pulses delivered per second, it follows that the current is proportional to the frequency. The linear relation holds up to about 7 000 cycles per sec., above which the linearity is affected in consequence of the capacitance across the diode load and the time-constants of the *RC* circuits. The upper limit is determined by the de-ionization time of the relays.

Typical examples of the application of such an instrument are the recording of rapid frequency variations occurring in speech and singing, the recording of the decay of artificial radio-activity, and frequency monitoring or control.

(9) USE OF VALVE OSCILLATORS FOR MEASURING PHYSICAL QUANTITIES

The change in frequency of a valve oscillator when the tuning capacitance is altered has been used for measuring changes in quantities such as length.* The change in length in the specimen is made to alter the capacitance of a parallel-plate condenser, and as the change in frequency can be determined very accurately very small changes in length can be measured.

As well as changing the frequency, a change in the tuning capacitance gives rise to a change in the impedance of the circuit and therefore in the amplitude of the oscillation. As the anode-current/anode-voltage and anode-current/grid-voltage characteristics of a triode are curved, anode-bend rectification takes place. Hence a change in the amplitude of the oscillation will give rise to a change in anode current, the anode current increasing when the amplitude increases. On the other hand, if the oscillator is self-biased, i.e. if a grid leak and condenser are used, the current through the grid leak will be approximately proportional to the amplitude of the oscillation. The grid current can therefore be taken as a measure of the amplitude. It will also give rise to an increased negative bias, so that the anode current in this case will decrease.

Several circuits have been described using the above methods for the determination of changes in physical quantities.† It has been shown that, by a suitable design of the oscillator circuit and the use of a sensitive current instrument, changes in length of about 10^{-6} to 10^{-7} cm. can be measured.

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* See Bibliography, (41).

* See Bibliography, (42).

† *Ibid.*, (43), (44), (45), and (46).

(10) USE OF VALVES FOR RESISTANCE MEASUREMENT

It has been shown that the grid-current/grid-voltage characteristic of a triode valve is approximately exponential for small currents. That is,

$$I_g = G\epsilon^{KV_g}$$

where V_g is the negative grid voltage and G and K are constants if the anode voltage is fixed.

If a resistance R is connected between grid and cathode,

then
$$\frac{V_g}{R} = -I_g$$

$$\therefore \quad -\frac{V_g}{R} = G\epsilon^{KV_g}$$

or
$$\log R = \log V_g + KV_g + \text{constant}$$

The anode current of the valve is determined by the grid voltage; therefore a definite relation exists between the anode current and the resistance R in the grid circuit.

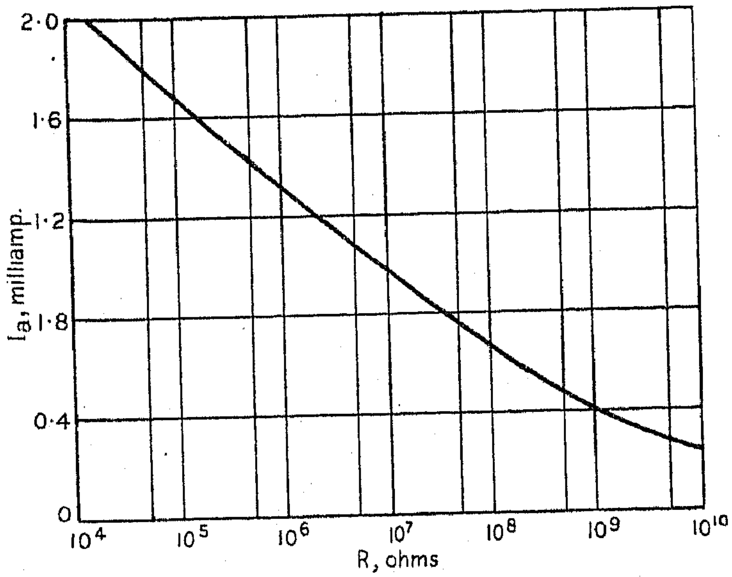

Fig. 32.—Relation between anode current and grid resistance for triode Type H63.

The method has been used for the measurement of high resistances.* Fig. 32 shows the relation between the anode current I_a and $\log R$, using a selected H63 valve. The slope of the curve changes very little for the range of resistance between 10 000 ohms and 100 megohms, and the order of accuracy to which the resistance can be measured is about 5 %. For values of resistance above 100 megohms the slope of the curve decreases, but the instrument can still be used as an indicator to show that a resistance is above a certain value.

If a high positive voltage is included in series with the resistance, very much higher resistances can be measured, and the voltage can be adjusted to correct for any change that might occur in the contact potential between grid and cathode.

(11) COMPARISON OF VALVE-OPERATED INSTRUMENTS WITH OTHER TYPES

The valve voltmeter, together with its application as a means of measuring current, is the most important of the various types of instrument which have been described, and it is interesting to compare it with alternative forms of instruments. The first instrument incorporating the thermionic valve—the valve voltmeter—was introduced mainly for high-frequency measurement where a high impedance was essential. Because of its unstable performance, poor scale shape, and difficulty of operation, together with the need for frequent recalibration, the early valve voltmeter was mainly confined to the laboratory for use by skilled observers. For several years, however, other types of instrument were unsuited to general high-frequency measurements with the exception of the thermocouple ammeter, which has maintained its usefulness as a laboratory instrument as a means of obtaining accurate comparison of alternating current with direct current. However, for voltmeters and ammeters of medium accuracy at radio frequencies, the chief disadvantages of instruments utilizing thermojunctions, namely small overload capacity, sluggishness of reading, and unsuitable scale shape for most purposes, have been overcome for many applications by recent improvements in metal-rectifier instruments. The latter are now made to read currents of several amperes up to the higher radio frequencies, and full-scale voltages from 1 volt upwards at frequencies up to 1 or 2 Mc./sec. The impedance of such instruments, while not of the same order as that of the valve voltmeter, is adequate for many purposes where small and inexpensive instruments are required.

A disadvantage often quoted in connection with valve voltmeters is the wave-form error to which they are liable. While it is true that in this respect these instruments compare unfavourably with thermal instruments, valve voltmeters are mostly used under conditions where the wave-form can be controlled. Thus, in those cases where they are used in conjunction with local oscillators, the distortion of the wave from sinusoidal form can be reduced to such small proportions that the wave-form error in the valve voltmeter is negligible. This applies especially to the series of instruments known as Q-meters, loss-factor meters, C-meters, etc., which consist of self-contained oscillators and valve voltmeters, the latter being calibrated directly in the quantity it is desired to measure. This application of thermionic valves in the field of electrical measurements is becoming increasingly important, not only for electrical measurements of all types, but also for the testing of the purity and properties of such materials as oils, insulating materials, and chemical substances by the direct measurement of their dielectric constant and power factor.

From this brief analysis it will be seen that the chief field of application of the valve-operated instrument is multi-range test equipment of medium size, associated in many instances with amplifiers and local oscillators in order that adequate range and flexibility of testing may be obtained. In the past, the valve-type instrument has had exclusive applications in the medium-frequency and high-frequency field, but, where low cost and very small size are essential, latest developments indicate that thermal and metal-rectifier types of instrument will meet many of the practical requirements for frequencies up to and including ranges commonly used for radio and carrier telephony transmission.

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* See Bibliography, (47).

(12) FUTURE DEVELOPMENTS

It is interesting to note that although the first reference to the use of valves for measurement purposes was made as early as 1916,* Dr. Drysdale made no mention of the thermionic valve as a factor in the future of electrical instruments in a paper entitled "Future Progress in Electrical Measuring Instruments," read before this Section 5 years ago. At that period, although the use of valve-operated instruments was considerable in the fields of radio and telephony, the thermionic valve was not considered to be important for general electrical measurements.

Since that time special valves have been developed for instrument applications, some of which have been described in the paper. The practical construction of valve-operated instruments has also been greatly improved; whereas formerly the valve voltmeter consisted of several components and controls, the modern instrument of this type is self-contained and is generally operated from a.c. mains. In overall size and portability it does not greatly vary from other multi-range test instruments, and the fact that an outside source of supply is required does not hamper its efficiency now that satisfactory means of controlling mains-voltage fluctuations are in widespread use.

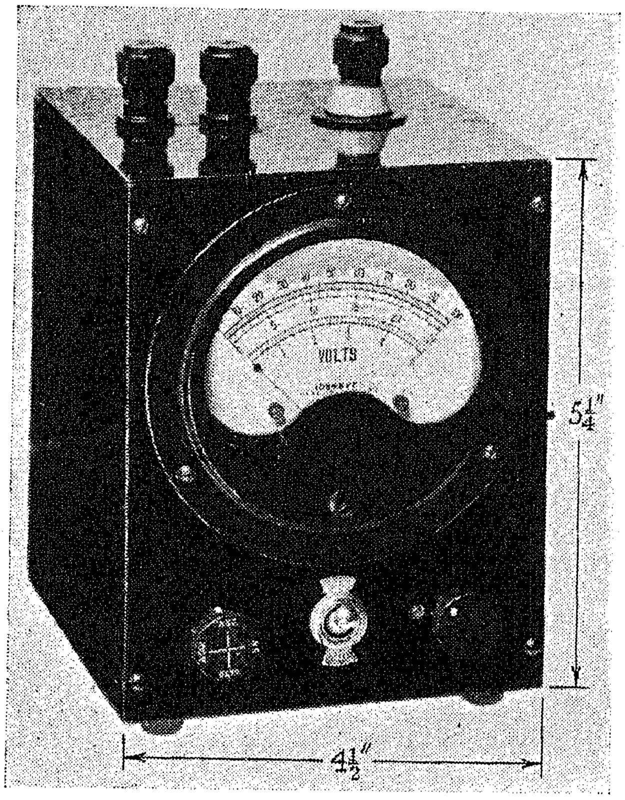

Fig. 33.—Small portable valve voltmeter.

Simple and inexpensive valve-voltmeters can be made to operate from pocket-lamp batteries, thus making a useful self-contained instrument with the general advantages of very high impedance and wide frequency range. An example of such an instrument is shown in Fig. 33.

One of the most important advances in the application of the valve to electrical measurements is the development of the negative feed-back amplifier. This opens up an extensive field of development in the construction of multi-range instruments with sensitive a.c. and d.c. ranges. In the past, instrument makers have striven towards the manufacture of more sensitive instruments by the use of new material, and improved mechanical construction of the indicating mechanism. While remarkable progress has been made in this direction, there is always the limiting factor of robustness; for instance, in the case of direct-current instruments, the use of portable galvanometers has enabled very small currents to be measured accurately for industrial as well as for laboratory testing. Such instruments are, however, always liable to damage by mechanical shock and electrical overload, and in the more sensitive types are affected by vibration, and appreciable time is required to take a reading. The stabilized valve amplifier has considerable possibilities both for sensitive d.c. measurements and for a.c. measurements, and has the advantages of robustness, portability, and flexibility of scale shape. Moreover, it is possible to make such an instrument with an almost unlimited overload capacity, a feature which is seldom available in other types of instrument, and which is specially valuable in sensitive multi-range instruments. In using such an instrument, the current or voltage to be measured can be connected to the terminals with the range switch in any position, and the switch position can be altered until a suitable reading is obtained. There is no fear of damaging the instrument by excess voltage or current up to the limit of the current-carrying capacity of the input resistances.

Such an amplifier-type valve-operated instrument has other important applications where the available power is very small. In particular may be mentioned the measurement of very high insulation values, and numerous applications in the extensive fields of sound, temperature, and light measurement.

This paper is a communication from the Research and Engineering staffs of the General Electric Co., Ltd., and the M.O. Valve Co., Ltd., at Wembley, and at the works of the Salford Instrument Co. The authors tender their acknowledgment to the General Electric Co. and the Marconiphone Co., whose research work on electrical instruments and valves has inspired this review.

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DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 6TH JANUARY, 1939

Mr. W. L. Beck: When the first valve voltmeters were produced, valves had to be selected and aged for long periods before they could be used in calibrated instruments. While the situation is better to-day, a period of ageing is often necessary to ensure that valves will maintain their calibration over a reasonable period of life. Where valves are made for instrument purposes, it would be an advantage if individual test figures were marked on a label attached to the valve by the manufacturer.

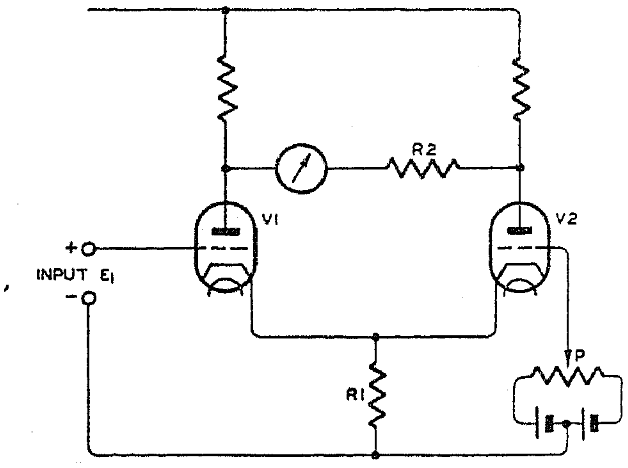

Fig. A

It is interesting to note that an analysis of the causes of failure of valve voltmeters over the last few years shows that over 80 % result from valve failure or loss of calibration due to change of emission. These figures apply to a voltmeter using an ultra-sensitive pivoted microammeter as the indicating instrument. It has also been noted that valves using an oxide-coated filament of the combined type, where the activating material is alloyed with the base, are more stable than valves using cathodes with the material pasted or painted on.

Dr. L. E. Ryall: The authors refer to the use of feedback to improve the stability of an amplifier. A difficulty arises with d.c. amplification, however, as it is not a simple matter to use a multi-stage d.c. amplifier, and this would often be required to compensate for the reduction of gain due to the feedback. Nevertheless, the arrangement shown in Fig. 24 can be modified to enable the stability due to the feedback to be obtained without loss of sensitivity. Fig. A shows a d.c. amplifier which is of the same form as that shown in Fig. 24. The two arms of the bridge are normally balanced by adjusting the

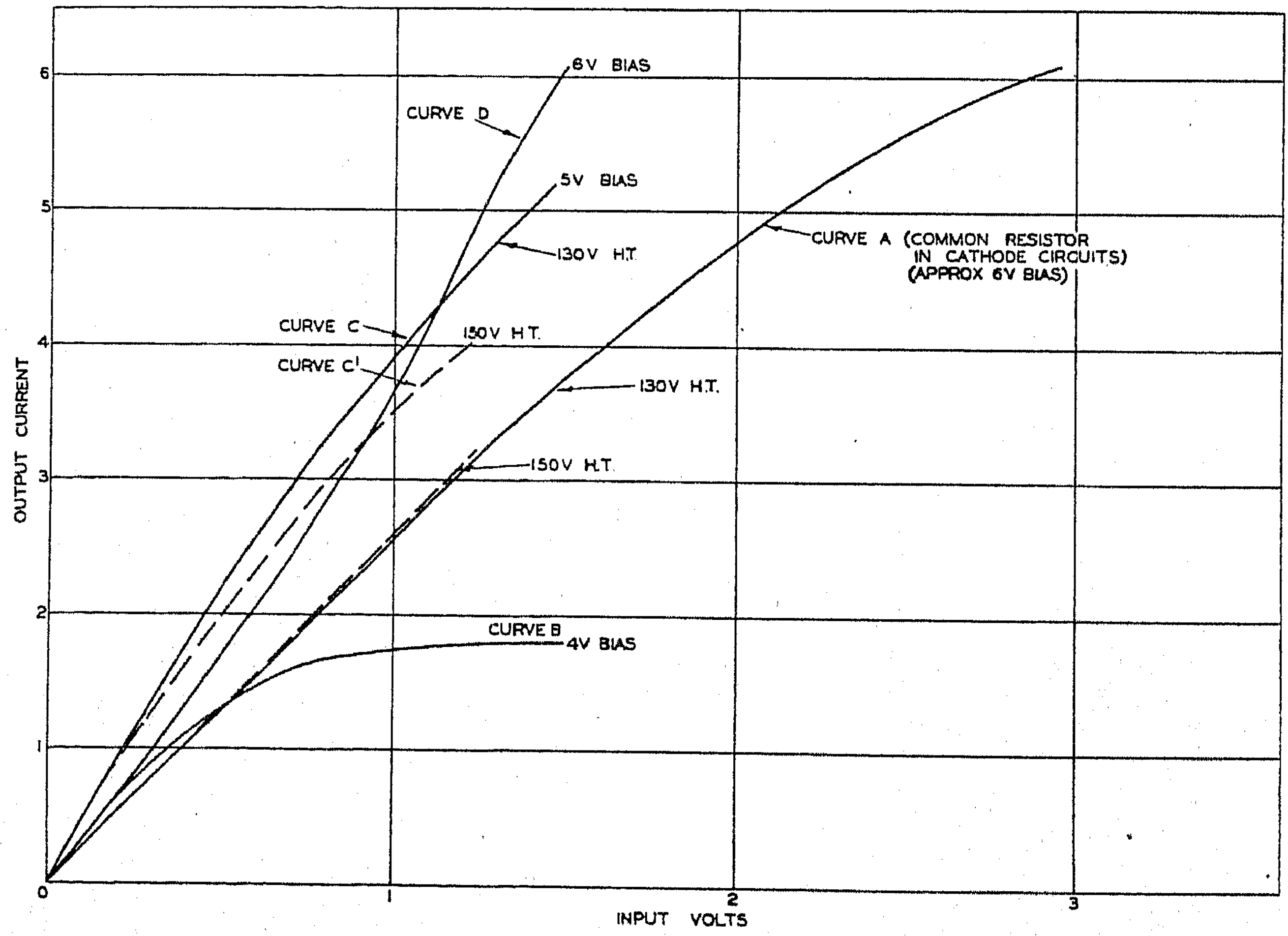

Fig. B

grid-bias potential of the valve V2 by the potentiometer P. An input voltage E_1 increases the anode current through the valve V1 and the common cathode bias resistor R1. The resultant increased negative grid-bias voltage decreases the anode current of the valve V2, and the current that flows through the resistor R2 is approximately the same as it would have been if the grid-bias potential had remained constant. A much greater degree of stability and also linearity of response characteristic has been obtained, as is shown in Fig. B. Here Curve A indicates the relation between input and output volts with the arrangement having the common cathode resistance. If the H.T. supply is changed from 130 to 150 volts the output remains practically unaltered. Curves B, C, and D were obtained using fixed grid-bias voltages, but the gain of the system has not been greatly increased. The characteristic, which is most nearly linear, is obtained with a 5-volt bias, but it is not stable with H.T.-supply changes, and the change from 130 to 150 volts alters the gain of the amplifier considerably.

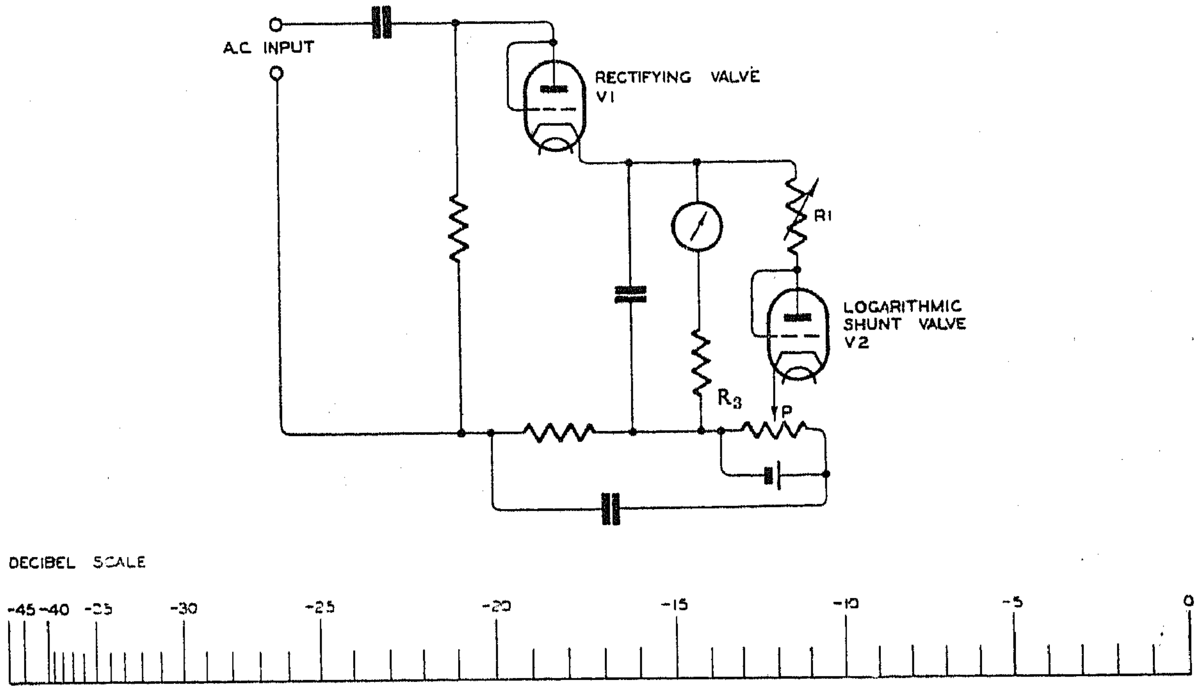

Fig. C

A thermionic voltmeter which incorporates a diode rectifying valve followed by a d.c. amplifier enables the rectifying-valve load to be of high resistance (1 megohm), so that the rectified current is only a few microamperes. The rectified voltage is then independent of the diode impedance, a condition which is not obtained when the rectifying-valve output operates a moving-coil meter directly.

A form of logarithmic voltmeter can be obtained by using the logarithmic property of the diode valve as indicated in Figs. 2 and 3. The valve is used as a logarithmic shunt. Referring to Fig. C, the valve V1 rectifies the signal and applies it to the microammeter in series with the high resistance R_3. An increase in the rectified signal causes the potential across the diode V2 to rise. The resistance of the diode falls and it shunts an ever-increasing amount of the rectified current. There are two variable factors in the valve used in this manner: (*a*) the voltage at which it starts to rectify, which can be controlled by the potentiometer P connected across a source of p.d.; and (*b*) the minimum value of the impedance that the valve tends to attain. This minimum value of impedance varies with different valves. If a resistance R_1 is connected in series with the valve so that a full-scale deflection is obtained with a certain unit input, the scale shape is practically independent of the shunt valve. The scale shown in Fig. C is reproduced to within ± 0·2 db. when an MH 4, MHL 4, or ML 4 valve is used, and to ± 0·1 db. or less with 50 % of the valves. Thus when this arrangement is used in conjunction with the d.c. amplifier shown in Fig. A a robust instrument is obtained, the scale shape of which is independent of the associated valve characteristics.

Dr. J. Greig: I should like to comment on the amplifier type of instrument, in particular that in which negative feedback is employed to ensure good linearity and constancy of characteristics.

This type of instrument is of particular value when a low-reading voltmeter or millivoltmeter of high impedance is required to give accurate indications on distorted voltage waves such as are encountered in iron testing. A true mean instrument based on this principle, reading down to about 0·02 volt for use in iron testing at 50 cycles per sec., has been found to give very satisfactory results. In this case the amplifier must, of course, give fidelity in respect of phase-shift as well as of amplitude up to the highest significant harmonic frequency.

Mr. L. B. Turner: I notice that the authors omit to mention two kinds of measuring instrument which fall within the scope they have selected for their paper. I refer first to the cathode-ray oscillograph. Of the valve voltmeter the authors say (page 248) that it "seems to be the most widely used instrument." Perhaps they are right for the moment; but I suggest that valve technique is forcing itself upon the rather reluctant attention of engineers outside the signalling field more through the oscillograph than even the valve voltmeter. It may be said, perhaps, that an oscillograph tube is not a valve within the meaning of the title of the paper: but even so, there is the linear time-base of the oscillograph, which is part of the measuring equipment, and one in which (in the words of the Introduction) " the thermionic valve is an essential component."

Second, I refer to the application of valves to the counting of rapidly succeeding events, after the manner originally proposed, I think, by C. E. Wynn-Williams. Counting, which is the quintessence of measurement, is there effected by gas-filled triodes, as in the frequency meter of Fig. 31.

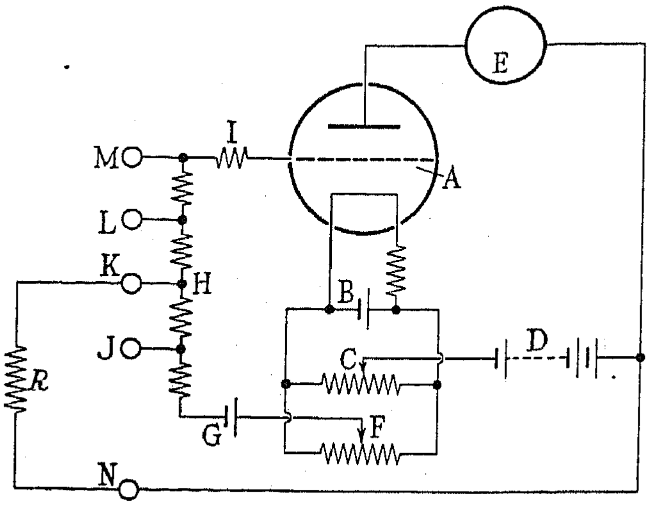

Fig. D

In Section (10), on the measurement of resistance, only one device is mentioned. This depends on the grid-current characteristic, and permits measurement of resistances over some such range as 0·01 to 100 megohms. In my view it is preferable to avoid dependence on a small grid current, if only because this current may be subject to uncontrollable factors such as contamination of the grid from the cathode, leading to appreciable thermionic grid emission. An alternative scheme is one I described in the *Journal of Scientific Instruments* (1935, vol. 12, p. 355). The principle is extremely simple (see Fig. D, which is taken from the patent specification). R is the unknown high resistance, and H is a tapped standard resistance of 11·1111 megohms. The grid of the valve is always sufficiently negative to make grid current negligible, but becomes the less negative the smaller is the unknown resistance R connected. The meter E, a 240-microamp. instrument, has a single scale of megohms running from 0·07 to 10; and multipliers 1, 10, 100, and 1 000 are given by the choice of terminal J, K, L, M for the unknown. The battery D consists of only five dry cells. With this the range of measurement is from 0·07 megohm to 10 000 megohms; and the range can be extended to 100 000 megohms by connecting an external 80-volt battery in series with the unknown resistance. The scale of the original megohmmeter is shown in Fig. E. (The lower scale is for an alternative use of the instrument as a valve voltmeter.) As the authors of the paper point out, a great virtue in valve-operated meters of this type is that they can be made undamageable by misconnections and so on. In this instrument no damage can be done in use whether by short-circuits, misconnections, or even the application of several hundred volts.

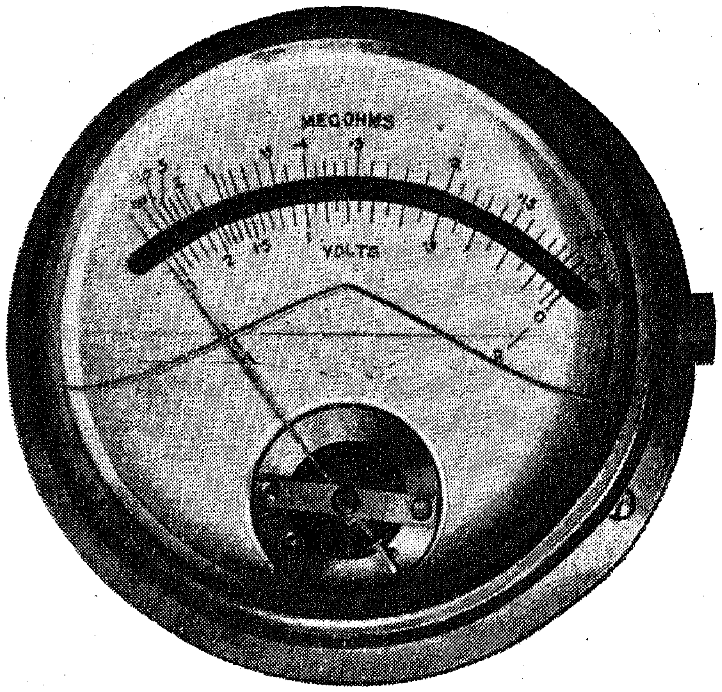

Fig. E

Dr. L. G. A. Sims: I should like to ask the authors whether they have experience of the design of the valve wattmeter, particularly in respect of its non-uniform behaviour with changing power factor. The difficulty I have in mind is the application of the wattmeter to the measurement of feeble iron losses.

Mr. E. C. S. Megaw: The authors refer to the suitability of the diode voltmeter for measurements at high frequencies, and particularly for measuring rather large voltages. This type of voltmeter can also be used, for example, with a bias voltage in series with the input terminals such that the d.c. output voltmeter is initially set to the most open part of its scale, to measure much lower voltages. The errors which arise at very high frequencies from the finite transit time of the electrons may be calculated with tolerable accuracy for voltages which are not too small. When, however, we are concerned with small voltages, the assumptions made in the calculations are no longer strictly valid, and we do not know precisely how great the transit-time errors in diode peak voltmeters may be at voltages from 1 to 10 volts.

The error due to the finite transit time of the electrons is directly proportional to the frequency and inversely proportional to the square root of the voltage being measured. This relation applies so long as the initial velocity of the electrons leaving the filament of the measuring diode is neglected; when, however, the measured voltage is low it is obviously unjustifiable to neglect the initial velocity, and the error then becomes smaller because all the work of getting the electrons across from filament to anode has not to be done by the voltage which is being measured.

It turns out from some measurements which we have made in the last few days that, with a diode voltmeter of the type to which the authors refer, the error instead of being inversely proportional to the square root of the voltage for voltages below about 50 volts becomes practically independent of the voltage. So that as a preliminary result we obtain this very simple rule that at voltages down to about 50 volts we must apply the known correction for transit time, and for lower voltages we simply take the value which would be calculated if the measured voltage were 50 volts. The method of obtaining that result may be referred to very briefly. It depends on the fact that we have found by means of measurements of the voltage distribution along perfectly uniform and concentric tubes that a certain arrangement of a thermocouple and a small series condenser acts as an accurate relative voltmeter. The combination of uniform line and thermocouple voltmeter provides an attenuator by means of which a small fraction of a known moderately high voltage can be applied to a diode voltmeter for calibration.

Mr. A. D. Blumlein: All the devices referred to in the paper have one point of similarity—the signals are applied at the grid and come out at the anode. It might be worth while considering where it might be advantageous to depart from this convention. One possible application of valve voltmeters is to the measurement of very high voltages. For this purpose one constructs a valve where the grid is earthed and used as a shield between anode and cathode. A very high voltage is put on a very small anode remotely situated from the grid, and in the cathode lead is put the inevitable feedback resistance, which is given a high value. In those circumstances the valve cathode rises to such a potential that there is practically no anode current. The valve acts as a potentiometer, the cathode voltage being about $1/(\mu + 1)$ of the anode voltage. At first sight this arrangement would seem to have no advantage over a resistance-type voltmeter, but the usual very high-voltage voltmeter resistances are cumbersome, and this arrangement will follow variations of the anode voltage quickly, so that measurements of very high voltage can be made in the comparative safety of a shielded cathode.

Dr. Ryall mentioned a case where one of his amplifier valves was fed in the cathode. I at first thought that he had provided us with a circuit of unlimited feedback and no loss of gain, but I now see that he has turned a single-phase amplifier into a push-pull amplifier.

Dr. R. W. Sloane: It has been suggested by several speakers that the least reliable part of an instrument incorporating a thermionic valve is the valve itself. They have described methods whereby variation, within limits, of the valve characteristics, may be made to affect the accuracy of the instrument but little. The limits have not been stressed, however. It must not be forgotten that the instrument ceases to operate when the valve fails. The user of the instrument knows this, yet usually he has no way of telling when the valve is working properly, or even whether it is still in its socket or not. It would add greatly to the convenience and confidence of users if some means were provided, in an instrument, of indicating whether the valve was functioning normally, or beginning to fail after its many hours of useful life.

Dr. H. M. Barlow: The question of the stability of valves for instrument purposes has already been raised. I should like to ask the authors whether in their experience the thoriated filament gives greater stability than the coated filament, and also whether the V-shaped filament which is generally employed nowadays is more inclined to produce unstable characteristics than the straight filament in a cylindrical anode. In my experience, of testing a number of valves for instrument purposes, I have found that there is nothing to compare in regard to stability with the straight thoriated filament placed along the axis of a cylindrical system of other electrodes. Perhaps the authors could give us some information on this subject.

Mr. M. G. Scroggie: Looking at this subject in a general way, it seems to me that there are two outstanding conclusions with regard to the use of valves in measuring instruments. The first is that the valve is unrivalled in certain respects, notably high input impedance and wide frequency range. On the other hand, it seems to be the most unreliable and unstable part of the equipment; and, notwithstanding the timely aid of negative feedback and a good deal of effort and ingenuity, it still cannot be put quite on the level of orthodox measuring instruments with regard to accuracy and stability of calibration.

It is possible to obtain the advantages of the valve without this disadvantage if the policy is adopted wherever possible of using the valve instrument only as an indicator, and depending for the calibration on some passive element in the circuit such as a resistance or capacitance. In laboratory applications, at least, it is usually possible to arrange that the quantity one wants to measure is given in terms of, say, the ratio between two resistances, which is a much more reliable thing than the calibration of a valve voltmeter. The valve voltmeter is then simply used for adjusting two signals at a certain point to equality.

(*Communicated*) In dealing with the slide-back valve voltmeter, the authors state that " as long as the characteristic is exponential, the value of the anode current is immaterial." If successful use is to be made of the instrument in practice, this statement must be qualified considerably.* The form of the anode current, when the alternating voltage being measured (" signal voltage ") is large, is a sharp peak lasting only a small portion of each cycle. Unless the anode-current reading (the mean value) is very small—say $0\cdot 5\,\mu$A or less—the amplitude of the peak must be considerable. This has three undesirable effects: firstly, the current peak corresponds to a considerable difference between signal voltage and slide-back voltage, which causes an approximately constant percentage error on all except small signal voltages, not shown in Fig. 14; secondly, the voltmeter must be designed for a large initial negative grid bias if this excess peak is not to run into grid current, and as the most suitable type of valve for an exponential characteristic has a close grid this necessitates a large anode voltage; thirdly, the relatively high peak anode current militates against protection of the microammeter by the method of limiting valve emission.

Mr. P. G. A. H. Voigt: I should like to refer to Fig. 20, which shows what is called a simple grid-leak voltmeter. Many years ago I required to measure the peak voltages to be applied to a power valve, to make sure that this valve would not be overloaded. The measurement was required for recording purposes, and therefore an unstable instrument was very undesirable. The arrangement which I used was almost that shown in Fig. 20, but with the resistance R omitted. With such an arrangement the triode becomes in effect a peak voltmeter which is capable of measuring quite small voltages or quite large ones, according to the type of valve employed. It will respond almost instantaneously to the peak, and will then recover in a time which depends on the various leakages in the valve itself.

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* For a fuller discussion of the point see M. G. SCROGGIE: " Radio Laboratory Handbook " (Iliffe), p. 90.

I aimed at getting a valve which would take approximately 5 sec. to recover, and to this end I spent many hours running-in new valves and scraping panels to make the resistances as high as possible. The authors now show a valve which they bias and then leave on for the rest of the evening, and there is no sign of recovery; so that valve technique has advanced considerably since the time when I did my work.

I should like, however, to emphasize that the simple circuit shown in Fig. 20, with the resistance left out and a suitably chosen valve, is a very convenient instrument for measuring peak a.c. voltages. Using the L.S.5 type of valve with 500 volts on the plate and a suitable anode resistance, it will operate a recording milliammeter very nicely, and will give an almost linear law up to about 45 volts (peak). Beyond that point, bottom-bend rectification takes place and the curve flattens out. By using small receiving valves with a low H.T. value one can obtain an almost linear characteristic for voltages down to a fraction of a volt. Below 0·5 volt there is a small deviation from linearity which is due to the initial electron velocity. When carrying out ordinary measurements, the only thing to make sure of is that the recovery time is sufficiently long for there to be no confusion between the successive crests of the waves which are being measured. Typical curves have already been published in the *Journal* (1932, vol. 71, p. 633).

Dr. E. H. Rayner: With regard to the valve wattmeter shown in Fig. 29, there are very considerable difficulties in obtaining accuracy when it depends upon the difference between two quantities which may be very nearly equal to one another. The difficulty increases when each of the quantities depends on three individual characteristics, as given in the equation on page 256. It is very unlikely that a_1, a_2, and a_3 will really be sufficiently exactly the same in two separate valves to give correct indications when used as a wattmeter at low power-factors, and what I would suggest is that anyone who tries the arrangement should interchange the valves and see whether the same results are obtained. If there are three or four valves, I suggest that they should be tried in pairs.

One would expect valves of the concentric type, with helical grid and cylindrical anode, to give more closely-agreeing characteristics than those of the flat type. The proof would be to see whether zero power-factor was indicated with a pure capacitance load.

Mr. R. S. Medlock: A certain amount of work has been carried out on the life of condensers at various working voltages, and a relationship has been obtained showing how with increasing applied voltage the probable life of a condenser will decrease. Is there a similar relationship in connection with valve life and applied H.T. voltage? It would be rather to the instrument-maker's benefit if he could reduce the H.T. voltage on the valve and so increase its life. Probably this would mean an extra stage of amplification and one extra valve, but it might be more economical to employ that second valve in order to obtain the increased gain with correspondingly increased length of life. If the authors can give any information on the relation between the probable life of the valve and its operating voltage, it will be of interest.

One question in which I am interested is what voltage the heater of an indirectly heated valve should be worked at to give maximum life. If it is under-run, is the life reduced?

[The authors' reply to this discussion will be found on page 268.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 14TH MARCH, 1939

Mr. G. J. S. Little: I was a little surprised to see that the equation given for the exponential part of a diode characteristic involved the value I_s—that is, the saturation current; the usual equation quoted for the 3/2-power part of the curve does not include the saturation current. I should have thought that the more nearly the saturation current was approached, the more potent that particular characteristic would be in determining the performance of a valve.

According to my recollection of what now seem to be the early days of valves, the LS.5, one of the first commercial valves with thoriated filament, followed closely on the R valve. The LS.5B was amongst the first commercial valves in which a close grid pitch was used in order to obtain a high amplification factor. I remember that in those days one looked at the characteristic curve of anode current against grid voltage and estimated what would be the middle of the straight part in order to fix the grid priming. Even now it is somewhat of a shock to me to see mutual conductance plotted against grid volts as in this paper for the LS.5A and LS.5B valves. The LS.5A was regarded as having a distinctly curved characteristic, but the LS.5 was thought to be above reproach. Since its curve of mutual impedance versus grid volts must lie between those of the LS.5A and the LS.5B one wonders how the curve of anode current versus grid volts could ever have been regarded as other than parabolic. However, I am pleased to see that in the standard valve characteristic there is still a straight part.

We have now had negative feedback for practical purposes since 1934, when Black's article was published (see item 5 of authors' Bibliography). To the telephone engineer who worked with valves prior to that date, I think the feedback amplifier will always remain something of a miracle because, short of removing the valve, one can hardly prevent the amplifier from giving its proper amplification. In the experimental field of telephony much use is made of networks of resistances to give predetermined amounts of attenuation. In the negative-feedback amplifier we have, as it were, the inverse of such attenuation networks; the amplification given by the negative-feedback amplifier, operating under the conditions for which it is designed, is almost as stable as is a network of resistance in regard to attenuation.

An application of negative feedback, described in the paper, which is new to me is its use in the direct-current case.

For some time I have felt that insufficient use was being made of the feedback principle in measuring instruments, but having read the paper, heard the remarks of the authors, and seen some of the instruments which incorporate negative feedback, I feel fully satisfied that negative feedback has definitely come into its own.

Dr. C. Dannatt: It is to be expected that valve-operated instruments should find their greatest use in the communication and radio fields. It is there that measurement problems demanding high input impedances and wide frequency-range usually occur, but it is nevertheless of interest to consider to what extent such instruments can be of use in the power-frequency field. It is difficult to find specific cases of this type of application. One which occurs to me is the measurement of average voltage in connection with the fixing of the maximum flux density in transformer testing. I have used average valve voltmeters for this purpose for many years and am surprised that the authors have not given examples of their use. It is not difficult, on the other hand, to find numerous examples of the application of valves to industrial measurement problems, where the valves are not used as measuring devices themselves but only as accessories for amplification and the like. In my experience the industrial applications which are most successful are of this type, provided the design is such that accuracy does not depend on valve characteristics.

Finally, I feel that the authors have dismissed rather summarily the question of supplies for the valves in valve-operated instruments. If voltage-regulation devices have to be included in the instrument a certain amount of reliability is sacrificed and maintenance troubles are increased. However, the time is long passed when such disadvantages of valves can be held to outweigh the advantages which they offer in many specialized measurement problems, and I must agree with the authors that, on the grounds of robustness and overload capacity alone, valve-controlled instruments are in many cases preferable to the delicate mechanically-controlled types.

Mr. G. M. Tomlin: I should like to mention two developments which appear to be of the utmost importance in carrier-frequency work. There has been developed—I think in America—a system of negative feedback which does not affect the overall amplification in the least, whilst at the same time straightening out frequency response. On the same subject the work of Mr. Ballantine in America would appear to be important. His method, by making use of reverse feedback, straightens out the valve rectifier characteristic and gets rid of the undesirable square-law portion. The methods might be quite important in carrier work, as they overcome the more undesirable features of valve voltmeters and the cramped scale at the lower end of the instrument.

Mr. F. Jones: I suppose that of all these measuring instruments using valve voltmeters, the most widely used, and really the most useful, is the peak voltmeter. This is of enormous practical value in all radio and high-frequency measurements, and is the only direct method available for measuring peak voltages.

The authors have described several kinds of peak voltmeters, and it would have been interesting had they indicated the particular uses for which each type of voltmeter is best suited. For instance, comparing the slide-back method and the diode method, we see from the curves in Figs. 14 and 17 that the accuracy obtainable is approximately the same. Presumably the diode type can be used for much higher voltages than the slide-back type.

Later in the paper the authors say that the general disadvantage of a valve-operated measuring instrument is liability to wave-form error, but using a diode in connection with a condenser does not seem to be a method which would be dependent on wave-form.

The feedback amplifier described in the paper could presumably, in addition to its other uses, be used in connection with the slide-back voltmeter. Since the output of the amplifier is independent of the circuit conditions, if it were thus used the errors due to the curve in Figs. 14 and 17, up to values of KE equal to 200, would be simply avoided if the amplifier were introduced between the voltage to be measured and the voltmeter.

The application of valves to the measurement of power is extremely interesting and ingenious. I think it would be of considerable use in telephone work and in radio work too, if it could be applied to low-power measurement. The authors give a figure of 10 milliwatts to a few hundred watts. I cannot see why the lower limit should be 10 milliwatts; there seems to be no prima facie reason why much lower powers should not be measured.

Mr. A. J. King: There are three points I wish to bring to the notice of the authors. The first one concerns the r.m.s. type of valve voltmeter. On page 245, in discussing the suitability of valves of various characteristics for use in valve voltmeters, it is stated that the quadratic range is best obtained with valves of low voltage factor, working at high anode voltage. These requirements suggest rather high anode currents. I should be interested to hear of the possibilities of using valves for measuring r.m.s. voltages with a very bad wave-form, covering a very large range in amplitude but calling for only small anode currents. The point becomes important in portable instruments where one cannot afford to have very large anode currents. At the same time the capability of measuring the true r.m.s. value with a very bad wave-form is desirable.

The second point concerns the problem of the thermionic noise which is developed in high-gain amplifiers. Have the authors developed any valves which are particularly suitable for working at the beginning of very high-gain amplifiers where it is important to reduce the noise of thermionic origin to the absolute minimum?

The third point is a practical one and concerns apparatus which is operated from a.c. mains and contains valves with the cathodes heated from the mains, and the difficulty of completely eliminating mains components from the output of these valves. This is particularly the case where one has a very high-gain amplifier operated from the mains. It is a fairly simple matter to smooth the H.T. supply as to cause no trouble, but one finds it extraordinarily difficult to prevent some small component from the mains getting into the output, through the cathodes, whether directly or indirectly heated from the mains. I should be very glad to hear whether any valves have been developed which can be used even at the beginning of amplifiers having amplifications of the order of 100 db., without introducing appreciable mains components.

Mr. E. Blackburn: Some years ago I had occasion to use one of the A.373 diodes in an attempt to measure the voltage across the tuned circuit of an oscillator working at 60 Mc./sec. Actually, though the leads were as short as possible the voltmeter readings obtained varied as much as 20 %, depending upon the position of the leads.

On page 247 the authors quote the impedance error at 100 Mc./sec. as 1 %, and on page 251 the overall accuracy of measurement is given as 3 %. These figures seem valueless when account is taken of the outside errors that are so difficult to avoid. I notice that the authors in applying this particular diode to the high-frequency circuit use a metal cover. The effect of a large piece of metal placed so near a high-frequency tuned circuit is automatically to alter the inductance and is bound to have an effect on the voltage developed.

I was interested in the comparison made in the paper between the hard and the gas-filled valve. The authors seem to favour the latter because of its freedom from error on readings below about 5 volts. I think that in practice the slide-back voltmeter is confined generally to measurements above that figure, because when one measures 5 volts or less it is much better to use the more convenient direct-reading type of Moullin voltmeter. In the circumstances, and considering the use of the slide-back voltmeter, it seems that the hard valve is to be preferred because of the higher impedance and lower absorption of power.

On page 259 there is a description of a very unusual method of measuring small alternating currents. The current to be measured is applied to the filament of the valve, and this valve is heated from a variable-frequency source of alternating current. The procedure is to vary this frequency and get the two sources into resonance by the zero-beat method; and it is stated that there is then a change in anode current due to the change of current in the filament. Figures are quoted to show the sensitivity. When the test current applied to the filament is 1 μA the anode current changes $0 \cdot 5$ μA. That is a very big change and I should be glad if the authors would explain it. The method seems to me to be very inferior to the one by Barlow, which is also described.

Mr. E. J. Johnston: When making interference-suppression measurements with a field-strength measuring set, the calibration of which could be readily checked as it relied upon the predominance of thermal-agitation noise over valve anode noise, it was found that a reduction of 3 inches in length of the condenser filter connecting leads increased the degree of suppression by the following:—

At 200 kc./sec. from 51 db., relative to 1 μV, to 44 db.
At 1 000 kc./sec. from 45 db. to 24 db.
At 6 000 kc./sec. from 82 db. to 57 db.
The last reduction is from 12 500 to 710 μV/m.

With the diode type A373 an added inductance due to external leads of $0 \cdot 1$ to 1 μH reduces the resonant frequency of the input impedance to 800 and 250 Mc./sec., respectively, and consequently the upper limit of operating frequency, for the same degree of accuracy, would be reduced from 100 to 80 and 25 Mc./sec., respectively. The difficulties which the authors have overcome can perhaps be fully appreciated when these alarming figures are considered.

THE AUTHORS' REPLY TO THE DISCUSSIONS

Dr. E. G. James and **Messrs. G. R. Polgreen** and **G. W. Warren** (*in reply*): The question of stability of valve characteristics to which several speakers have referred is, naturally, one which is of considerable importance to instrument makers, and, while improvements during the past few years have been considerable, it must be admitted, as Mr. Scroggie points out, that the valve cannot be regarded as entirely satisfactory in this respect. Stability is, however, a relative term, and instrument designers sometimes ask for more than may be reasonably expected. Where, for example, the standing anode current of a valve is balanced out and a very sensitive instrument is used for measuring small changes in anode current, complete freedom from "zero drift" is very difficult to achieve unless compensating circuits are employed. Close co-operation between valve and instrument makers during the development of instruments is very desirable and will often prevent disappointments at a later stage. In particular the practice, sometimes adopted, of designing an instrument around a single sample valve should be avoided. With regard to Mr. Beck's suggestion, the valve maker is always willing to give individual test figures for valves when asked to do so, but the reason for not making this a general practice for all valves used in instruments is that the valve maker does not always know the conditions under which the valve is to operate, or whether the particular characteristic he would normally measure is the one required. Although valves with oxide-coated filaments of the combined type to which Mr. Beck refers are not in common use, we would expect that under suitable conditions, e.g. low electrode temperatures, these might be more stable than valves with paste cathodes. Valves with thoriated tungsten filaments are certainly more stable than those with oxide-coated filaments, and particularly in the rather exceptional cases where the cathode is required to operate with saturated emission. Several years ago one of the authors attempted to produce a diode with an oxide-coated filament, suitable for a saturated-diode ammeter described by Dr. Barlow. By exercising special care in pumping and activation satisfactory valves were, in fact, made. The valve maker could not, however, feel confident of being able to reproduce such valves over a period of years, particularly if the demand for such valves should increase to such an extent as to necessitate the use of another batch of raw material. The greater stability which Dr. Barlow has noticed in valves using straight, rather than V, filaments, is probably due to slight changes in thermal conduction at the spring contact in the latter type. This difficulty can be overcome by welding the spring to the filament, a practice which has been adopted in certain cases.

Referring to the points raised by Mr. King, it is true that the closest approximation to a parabolic characteristic is obtained with valves having low amplification factor and working at high anode voltages, and large values of grid bias are then necessary to keep the anode current at reasonably low values. High anode voltages are not, however, absolutely necessary, as will be seen from Figs. 6 and 8, and for portable instruments it will be found that small battery-operated power valves will operate satisfactorily at quite low values of anode voltage and current. The characteristic of the type P2, for example, is approximately parabolic for anode currents between 1 and 8 mA even with an anode voltage as low as 50 volts. With regard to thermionic noise and mains hum, special valves have been developed for use in high-gain amplifiers. In the triode type A537, special insulators are employed to reduce to a minimum the noise due to leakage. In type A980, which is also a triode, the ratio of mutual conductance to anode current is higher than in A537, so that the thermionic noise referred to the grid circuit is even less; the design of heater and the high heater-cathode insulation in this valve are such that mains noise is extremely low. A special tetrode, the A863, has also been developed in which microphony and hum are extremely low: this type is suitable for use in amplifiers having a gain of about 110 db. Certain standard valves which have a high ratio of mutual conductance to anode current, such as the tetrode KTZ41, are also suitable for the first stage of a high-gain amplifier if direct current is used for the heater; but neither in this valve nor in the A980 have the same precautions been taken to reduce leakage currents to an absolute minimum.

Mr. Little has referred to what, at first sight, seems to be a surprising property of the diode characteristic shown in Fig. 1, namely that the factor I_s, the total emission of the cathode, appears in the formula for very low anode currents but not in the expression for higher anode currents. This arises from the fact that the mechanism of control is quite different in the two cases. With a retarding voltage V on the anode, then, if the current is so small that the space charge is negligible (this will be so in most cases for values of V numerically greater than about 0·5 volt), only those electrons with energies greater than eV electron-volts will reach the anode. With the cathode at a constant temperature a change in the total emission of the cathode will result in a proportional change in the number of electrons leaving the cathode per second with energies greater than eV, and therefore in the anode current. With a positive voltage on the anode, however, all the electrons from the cathode, whatever their initial velocities, would reach the anode, were in not for space charge which is the controlling factor and which limits the current to a value dependent almost entirely on the geometry of the electrode system and on the electrode voltages. Initial velocities do, in fact, have some effect, but this is small when the current is an appreciable fraction of the total emission.[*] Thus, both at the bottom and top end of the characteristic shown in Fig. 1 the effect of total emission is considerable, while over a certain region, CD, the current is independent of total emission.

It is not easy to give a definite answer to Mr. Medlock's questions on valve life. There are so many factors, including cathode temperature, anode dissipation, anode voltage, cathode current, residual gas in electrodes, and efficiency of the getter, which determine the life of a valve that one cannot predict with certainty what will be the effect of varying any one of them in a particular case. While, for example, a decrease in cathode temperature will reduce the rate of loss of active material and under ideal conditions will improve the life, it also makes the cathode surface more sensitive to " emission poisoning " by traces of residual gas. The cathode temperature chosen for a particular type depends on the normal purpose for which the valve is designed. In general, however, the rated temperature of modern oxide-coated cathodes is such that a life of several thousand hours can be expected from them and little if anything can be gained by under-running. Some advantage will, however, often result from a reduction in anode dissipation, particularly in power output valves, together with, in the case of tetrodes and pentodes, a reduction of the power expended in the screen.

Mr. Turner has referred to two other types of instrument, the cathode-ray oscillograph and counting instruments. With regard to the former, although the applications are numerous we do not think they come within the scope of the paper. The linear time-base circuits frequently employed come rather under a similar heading to oscillators, which we have excluded. We are, however, inclined to agree that valve counters might, with advantage, have been included. An excellent review of this subject has been given elsewhere by Wynn-Williams.[†] With reference to Mr. Turner's comment on the measurement of resistance, no difficulty should be experienced due to grid emission if a suitable choice is made of the type of valve and operating conditions. The alternative method which he suggests is, however, interesting and provides a compact instrument capable of measuring a wide range of resistances.

We agree with Dr. Ryall that the use of multi-stage d.c. amplifiers presents difficulties; the arrangement which he shows in Fig. A is extremely interesting. It would appear that, in order to obtain zero stability with changing supply voltage, fairly close matching between the mutual conductances of the two valves at a given anode current is necessary. An alternative method which has been used, of obviating the necessity for a d.c. amplifier, is to chop the input by some form of interrupter and use a multi-stage a.c. amplifier. Ginzton, in a recent article,[‡] claims that the reduction in gain due to negative feedback can be avoided without loss of stability by the additional application in a bridge circuit across the input of what is described as " positive feedback." This is, presumably, the paper which Mr. Tomlin had in mind when he referred to a system of feedback which does not affect the overall amplification. With regard to the logarithmic voltmeter using a diode shunt, it should perhaps be pointed out that, although the triode characteristics of the MH4, MHL4, and ML4 valves are very different, the diode characteristics, when the anode is connected to the grid, of these three types do not differ very widely.

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[*] C. Fry: "The Thermionic Current between Parallel Plane Electrodes; Velocities of Emission distributed according to Maxwell's Law," *Physical Review*, 1921, vol. 17, p. 441.

I. Langmuir: "The Effect of Space Charge and Initial Velocities on the Potential Distribution and Thermionic Current between Plane Parallel Electrodes," *ibid.*, 1923, vol. 21, p. 419.

[†] C. E. Wynn-Williams: "Electrical Methods of Counting," *Reports on Progress in Physics* (published by the Physical Society), 1936, vol. 3, p. 239.

[‡] E. L. Ginzton: "Balanced Feedback Amplifiers," *Proceedings of the Institute of Radio Engineers*, 1938, vol. 26, p. 1367.

A linear decibel scale has proved to be of considerable advantage, especially in connection with telephone transmission measurements. To obtain an approximation to such a scale on pivot-type instruments it is usually necessary to have recourse to moving-coil instruments with shaped poles which give an approximately logarithmic scale but result in uneven damping. With the type of instrument shown in Fig. C, however, a close approximation to a logarithmic scale is obtained, but we have found that the advantages of such an arrangement can only be fully realized if a suspension-type galvanometer is used. Pivot-type instruments do not appear to be sufficiently sensitive.

With regard to Dr. Rayner's queries on the valve wattmeter, it is very probable that small differences between valves will occur in practice. The effect of such differences has been investigated by Mallet,* who shows that they can be compensated for by adjusting the anode battery tap away from the mid-point of the shunt across the meter. The meter will then have a zero error, but this can be eliminated by a zero adjustment. It would be advisable, however, to re-calibrate the instrument if valves are changed. No information is available as to the behaviour of the instrument with very low power factor, but Mallet shows that it is satisfactory for power factors from 0·5 leading to 0·5 lagging. Referring to the remarks of Mr. Jones on the lower limit of power which can be measured with a valve wattmeter, it will be seen from the formula on page 256 that the sensitivity is determined by the value of the coefficient a_3, the magnitude of the resistance R and, of course, the sensitivity of the meter in the anode circuit of the valves. High values of a_3 are associated with valves having high amplification factor and mutual conductance, and the upper limit to R will be fixed by the permissible error due to the power absorbed in this resistor. The sensitivity of the output meter will determine the robustness and stability of the instrument.

In reply to Mr. Jones, the choice of peak voltmeter for any particular use depends on factors such as the amplitude of the voltage to be measured, the input resistance of the voltmeter, and the impedance error. In measuring small voltages of low frequency, where a calibration of the instrument is not possible and where input impedance is not important, a slide-back voltmeter using a gasfilled triode would be better than any other type; but when the power absorbed by the voltmeter must be small, then a hard valve would be more suitable. As has been pointed out in the paper, one of the limitations in measuring voltages of high frequency is the impedance error due to the input capacitance of the valve and the inductance of the connecting lead. The smaller the input capacitance the higher the frequency at which measurements can be carried out with accuracy, and it is here that the diode peak voltmeter scores over all other types.

When a diode peak voltmeter is used for measuring large voltages the wave-form error is negligible, but this is not the case at low voltages. The curves showing the efficiency of rectification in Fig. 17 have been calculated assuming a sinusoidal input, and the shape of these curves would depend on the wave-form of the voltage. A feedback amplifier can be used to precede a voltmeter, but a difficulty arises in making the amplifier gain constant over a sufficiently wide frequency range.

With regard to Dr. Dannatt's remarks on the use of a valve voltmeter for measuring average voltage, such an instrument is referred to on page 252. The voltmeter employs negative feedback and is specially designed for measuring mean values of a distorted voltage which are met in transformer testing.

The use of negative feedback dispenses, to a large extent, with the need of voltage-regulating devices. However, when the voltage supplies are obtained from the a.c. mains, a saturated core transformer will give added regulation without any sacrifice in reliability.

In making voltage measurements at very high frequencies, it is important that the connecting leads to the voltmeter should have as low an inductance as possible. If this is not the case, a voltage will be developed across the earthy lead, due to earth currents, and the reading of the voltmeter will be altered. The metal case, housing the diode in the voltmeter described, enables the connection to be made via concentric leads, and the quoted accuracy of 3 % at 100 Mc./sec. was obtained experimentally using concentric leads.* It seems possible that the large variations observed by Mr. Blackburn may have been due to earth currents.

Referring to Mr. Scroggie's comment on the slide-back voltmeter, we agree that it is desirable to keep the mean anode current small in order to ensure that the positive peak of the voltage wave does not exceed values of grid voltage beyond those for which the exponential relationship holds. Provided this condition is satisfied, however, the statement that " the anode current is immaterial " needs no qualification.

With regard to the current meters described on page 259, both the Barlow and the Martyn type use a diode valve operated under saturation conditions. Barlow superimposes the alternating current to be measured on a direct current, so that the total effective heating current is

$$I = I_f + \frac{i^2}{2I}$$

where I_f is the direct current and i is the r.m.s. value of the alternating current. In Martyn's method, however, the main heating current is alternating, and when this is in phase with the current to be measured the effective heating current is

$$I = I_f + i$$

where I_f and i are the r.m.s. values of the two currents.

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* See Bibliography, (38).

* See Bibliography, (4).

Now with the oxide-coated filament used in the latter case a 1 % increase in heating current gives rise to approximately 10 % increase in emission. Martyn's filament current was between 50 mA and 100 mA with an emission of about 5 mA, so that a change of 1 μA in heating current would be expected to give a change of $\frac{1}{2}$ to 1 μA emission, which is in close agreement with the figure he quotes.

The provision of some means to indicate whether or not a valve is functioning normally would, in general, add complications to the instrument. It must be remembered, however, that Dr. Sloane's criticism does not only apply to valve instruments, and the only really satisfactory method of overcoming this objection is to re-calibrate the instrument.

DISCUSSION ON "THE LONDON TELEVISION SERVICE"* AND "THE MARCONI-E.M.I. TELEVISION SYSTEM"†

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 28TH NOVEMBER, 1938

Prof. E. W. Marchant: I should like to say a word or two about the developments that have taken place which have enabled television transmission to come about. It is not much more than 30 years since the cathode-ray oscillograph was first used in laboratories as a rather specialized scientific instrument, and those of us who remember the difficulties of the experiments that were made in those days will appreciate the immense amount of hard work and scientific investigation that has been needed to produce the apparatus that sends out and receives television to-day. At the University of Liverpool we have made during the last few years a number of experiments with short waves, and we know some of the problems that are involved in their production.

One point of interest is that no less than five microphones are used for a sound broadcast. This means that when one is listening to a broadcast, say, of a concert, one is getting something that one cannot get if one attends the concert. The broadcast version is obtained from a number of microphones in specially arranged positions in the hall, and is therefore a better result than is heard in the hall itself.

I remember seeing the first transmissions that were sent out from Alexandra Palace, in October, 1936. The pictures were extraordinarily good, and no one could wish to have pictures with better definition than we have to-day. The chief criticism that has been made by "viewers" is that the size of the picture is too limited.

I do not think this criticism is justified. Considerable efforts have been made to produce large-scale television pictures, but it seems to me that such pictures would be no advance on what one already gets with the cinema.

The technique that has been developed in connection with television "productions" is one which is only just beginning. As time goes on, we shall realize the possibilities of television far more than we do at present.

I am very interested in Fig. 18 of the paper by Messrs. Macnamara and Birkinshaw, showing the range of transmission round London. Many years ago we found that with short waves transmitted over short distances the kind of thing that produces weakening of the signals is a comparatively small obstacle.

Has any television transmission been received at long range, say in South Africa?

Mr. E. J. Johnston: I should be glad if Messrs. Macnamara and Birkinshaw would confirm that in the case of the Marconi sound transmitter the master oscillator works at half the carrier frequency, and not at twice the carrier frequency as is stated on page 745 (vol. 83). It is noticed that a stability of ± 1 part in 100 000 is claimed: does this refer to a time period of 24 hours? Is the idea of feeding the master-oscillator filament from a mains-driven rectifier to enable it to be continuously worked, so as to avoid frequency variation?

It would appear that neither the sound nor the vision transmitter is crystal-controlled. In view of the fact that it has been found possible to grind crystals down so as to resonate at frequencies as high as 60 Mc./sec. with a practically zero frequency-temperature coefficient, perhaps the authors will explain why such crystals are not used.

Mr. G. H. Rawcliffe: First, we are told that the maximum modulation frequency is 2·5 Mc./sec. On what basis was this chosen? In sound transmission the desirable modulation frequency has a definite upper limit, this being the frequency of the highest harmonics in the sound wave which are audible to the human ear. In vision transmission it seems to me that there is no such obvious upper limit due to the properties of the human eye, and that the brightness of the picture might vary in space at any rate whatsoever. Now a modulation frequency of 2·5 Mc./sec. and a line frequency of 10 125 lines per sec. give a maximum of about 250 modulations per line, and it is this value which I should like the authors to justify.

Secondly, I understand that the sensitized surface of the Emitron camera consists of a number of discrete particles

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[*] Paper by Messrs. T. C. Macnamara and D. C. Birkinshaw (see vol. 83, p. 729).

[†] Paper by Messrs. A. D. Blumlein, C. O. Browne, N. E. Davis, and E. Green (see vol. 83, p. 758).

and I should like to know, roughly, the particle density, and whether this causes any irregularity, or is in any way connected with the modulation frequency.

Lastly, Mr. Blumlein, in Section (4) of the paper, suggests that phase modulation was contemplated instead of amplitude modulation. What factor in vision transmission caused this reversal of sound-transmission practice to be considered, and why was it finally abandoned?

[The authors' replies to this discussion will be found on page 274.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 5TH DECEMBER, 1938

Dr. J. Greig: The points which I wish to raise are concerned primarily with the output stages of the transmitter.

It would be interesting to know whether the adoption of the conventional neutrodyne bridge for the final stage was determined by the fact that suitable water-cooled pentodes were not available commercially at the time the transmitter was designed.

Does the phase displacement for the extreme side frequencies shown by the half-ellipse in Fig. 22 of the paper by Messrs. Blumlein, Browne, Davis, and Green, represent a limiting value of phase-shift which can be tolerated, or is reduction in amplitude still the significant factor?

Two further points of general interest: would it be possible to mention the form of circuit in which the synchronizing pulses are added to the vision signal; and is any special technique, such as the use of a specially built "picture" tube, employed in the transmission of the present standard tuning pattern?

Mr. J. A. Cooper: Having had no personal experience of television or short-wave transmitters, I propose to limit my remarks almost exclusively to the paper by Messrs. Macnamara and Birkinshaw, and to confine them to less specialized matters.

On page 737 (vol. 83) it is stated that, in effect, a television programme is produced before an audience. This being so, one might expect the parallel to a theatre footlights system.

On page 738 it is stated that high-angle lighting is supplemented by spot lamps at floor level. Fig. 7 indicates that these lamps are few in number. It would be interesting to know why the bulk of illumination is of the high-angle type when footlights and general frontal lighting might be expected to give a brighter image in the Emitron.

On the same page it is stated that experiments are to be carried out to determine the suitability of lamps of the water-cooled gaseous-discharge type. As the paper was written in 1937, these experiments have by now probably taken place, and it would be interesting to have an account of the results.

On page 741 it is stated that controls are introduced which take account of the finite time of transmission of the scanning wave-forms and vision signals along the camera cables. Some information regarding the design and operation of these controls would be of interest.

Mr. Blumlein refers in detail to line- and frame-synchronizing signals. Nothing is said in either of the papers to indicate how these signals affect the receiver. They obviously allow time for the flyback operations to take place, but, as the signals are so carefully arranged, I feel there must be some reason why such particular care is taken regarding the various impulses. Could some more information be given on this point?

Mr. S. T. Stevens: In the Emitron camera, by suitably altering the amplitude of the line- and frame-scanning pulses, it is possible to cut down the area of the picture which is being scanned on the mosaic in such a way that if the head and shoulders of a person were normally in the centre of a rather large area of screen the reduction in mosaic scanning would pick out the head and shoulders only of the subject. This would be the equivalent of tracking the Emitron camera forward, although there would be no actual movement. I should be interested to learn whether this practice is in use at Alexandra Palace.

I understand that in the Super-Emitron camera the primary electrons are projected in the optical plane down the tube from what is actually a photocell combination at the front of the tube, and are made to strike a mosaic which is normally photosensitized. It is understood that this mosaic need not be a true mosaic as in the case of the ordinary Emitron camera and that a plain mica plate may be used. Secondary electrons evidently have to be released from this plate to effect the amplification used in the Super-Emitron, and I should like to know how this comes about without there being any secondary-emissive material on the signal plate.

In connection with mechanical receivers, it was found that the original synchronizing pulses given out by the B.B.C. signals were not quite suitable for synchronizing mechanical scanners at the receiving end. I should like to know what changes were afterwards made in the transmitted envelope form of the synchronizing signals, to avoid this difficulty.

Mr. W. R. Bowler: It is understood that the cable used for outside broadcasts must have a very low attenuation factor. The apparatus used for testing the cable sections with a view to balancing these losses must therefore have a high degree of efficiency. Can any information be given as to the type of apparatus used for this purpose, and the degree of accuracy achieved?

Mr. A. E. Stollard: What is the greatest distance over which television has taken place, and what are the possibilities of the range being extended?

Mr. W. Hawking: I should like to know what is the field-strength value necessary for adequate reception of television, and whether this value is directly dependent on the maintenance of an optical path. Is the strength of the field the vital factor determining the limit for satisfactory transmission, or is the high interference/signal ratio that would be experienced at a distance from the transmitting station a more important consideration?

In the southern part of the area shown in Fig. 18 of the paper by Messrs. Macnamara and Birkinshaw we have two contours around Sanderstead and Sutton where high ground exists and where the field strength is approximately 1 to $1\cdot25\ \mu$V per metre. I should have expected that beyond the high ground on the remote side of the transmitting station the field strength would have fallen away very rapidly, but, on the contrary, it appears to be stronger here than at other points which are at the same radial distance from the transmitter and are less heavily screened.

With regard to the transmission of television by wire and cable, I should be glad of some information as to the difficulty which is being experienced in using the coaxial cable for the transmission of television programmes from London to, say, Birmingham. Is the major difficulty the difference in transmission time between the extreme frequencies necessary for the transmission of the television frequency band?

Mr. H. Joseph: I notice that the figures chosen for the number of lines are all a multiple of 3. For the experimental transmission the number of lines was 30, which is 3 × 10; in the next attempt the number was 180, which is $3^2 \times 20$; the next 243, which is 3^5; and the final one is 405, which is $3^4 \times 5$. Perhaps Messrs. Macnamara and Birkinshaw would give us the reason for this.

Mr. D. R. Parsons: I notice that in the experimental Baird transmitter used before the Marconi-E.M.I. apparatus was finally decided upon, the original radio frequency was about 1·4 Mc./sec.; and on the mobile transmitter and the Alexandra Palace transmitter now used by the B.B.C. the original operating frequencies used by the master oscillator are 32 Mc./sec. and 22·5 Mc./sec. respectively. This means only one stage of doubling followed by the radio-frequency amplification. It would be interesting to know why such high freqencies were chosen.

The authors do not mention what type of circuit is used in such exceptionally high-frequency master oscillators. For the portable transmitter a stability of 1 part in 5 000 is specified. This is rather a poor stability, but it may be quite satisfactory in view of the large bandwidth of the receivers used and the absence of any other transmitters on neighbouring frequencies.

I notice that the local sound and vision aerials cause a signal of 10 volts to be induced across the input terminals of the receiver used for picking up the signals from the mobile transmitter working on 64 Mc./sec. A filter is used to cut this voltage down by 70 db. Would the addition of a signal-frequency high-frequency stage simplify the design of the filter and also enable some of the more distant outside television broadcasts to be picked up more efficiently?

Mr. T. D. Wright: Messrs. Macnamara and Birkinshaw's pictures of the studio arrangements indicate that the lighting is flooded all over the setting. As the definition in television reproduction depends on the light and shade, would it not be more suitable for transmission and possibly give more definition in the received picture if the light were concentrated, so that the shadows showed up on the forms?

Mr. M. E. Tufnail: Messrs. Macnamara and Birkinshaw refer to the arrangement of lighting employed to produce an illusion of depth. Since the pictures are received on a flat surface, it is difficult to appreciate how the illusion of depth can be given.

The whole subject of television transmission appears to be complicated by the necessity for scanning and synchronization. It has been mentioned that the start of television comprised the invention of scanning, and I should like to ask whether any systems have been contemplated which would not involve scanning. I would point out in this connection that the great majority of early systems of telegraphy involved synchronization of the transmitter and receiver, but these have since been superseded by systems which do not necessitate synchronization.

Mr. C. R. Jephcott: In connection with the frequencies chosen for the sound and vision transmitters, namely 41·5 and 45 Mc./sec. respectively, it would be interesting to learn whether the separation of 3·5 Mc./sec. has been found sufficient in practice to prevent side-band interference completely between the two signals. Is the service area of the station likely to be affected to any appreciable extent for greater power output from the transmitters?

With regard to the mobile ultra-short-wave vision transmitter, will Messrs. Macnamara and Birkinshaw indicate the approximate useful range of this unit.

Lastly, what is the average expected life of a cathode-ray tube as used in a standard television receiver, employing, say, a 12-in. diameter tube giving a 10 in. × 8 in. picture; and what is the screen size adopted in the monitoring equipments used at the London Television Station?

Mr. P. E. Farren: Mr. Blumlein refers to the advantages obtained by interlaced scanning. Apparently only a double interlace is used, and I should like to know whether consideration has been given to triple or quadruple scanning, and whether such scanning would give improved results.

Mr. H. Faulkner: From the design details given in the paper by Messrs. Davis and Green it seems that the plan has been to take a particular valve and work at the maximum power output which can be obtained. This seems to be a reversal of the normal process of design, in which one would have expected a particular power output to have been decided upon and the valve transmitter to have been designed in such a way as to give this power output. It seems to become a question of the design of a suitable filament when given the required emission, which is not a very difficult problem. There may, however, be limitations in the practical design of this type of valve for use at these frequencies, and it would be interesting if the authors would indicate what are the present limits of development in this direction.

As regards the arrangements to ensure that the frequency of the frame is held in synchronism with that of the grid supply, I should be interested to know whether the hour-to-hour variations which must occur in the frequency of the grid supply are sufficient to cause any trouble. The number of cycles generated by grid stations is a fixed quantity over a particular period of time. This is made possible, it is understood, by a slight speeding-up or reduction in frequency from time to time.

The use of demountable-type screen-grid valves on the Baird system of television described in Messrs. Macnamara and Birkinshaw's paper is of interest. Valves of this type have also been used in the short-wave transmitters of the Post Office, and were in fact developed by the Metropolitan-Vickers Electrical Co. for that purpose at the request of the Post Office. The feature of this kind of valve which allows more flexibility in electrode design, especially during experimental stages, is a very useful one, and screen-grids have obvious applications in short-wave work.

Mr. J. J. E. Aspin: I should like to know whether the authors have conducted experiments on the spacing of directors and reflectors in the case of television receiving aerials and the transmitting arrays used at Alexandra Palace, and, if so, whether the findings were in agreement with those of G. H. Brown,* who suggests spacings less than a quarter of a wavelength in the case of simple dipole aerials.

Mr. H. G. S. Peck: One cannot but be struck by the enormous amount of work which has been done in developing television in a comparatively short time. While television is an extension of sound radio-communication and telephony, it is a very great advance in every way upon what has already been done in these two branches of electrical engineering.

The Post Office has provided a system of special cables for outside television broadcasts connecting strategic points in London with Broadcasting House and Alexandra Palace; it is interesting to learn that it is possible to extend this by the use of a link consisting of ordinary telephone cable up to 2 miles in length if it is suitably equalized.

The authors say very little about the coaxial cable which has been laid between London, Birmingham, and Manchester. If television becomes at all popular, I can imagine that the Post Office engineers will be very busy in doing what they can to eliminate interference.

THE AUTHORS' REPLIES TO THE DISCUSSIONS AT LIVERPOOL AND BIRMINGHAM

Messrs. T. C. Macnamara and D. C. Birkinshaw (*in reply*): Prof. Marchant inquires whether any television transmission has been received at long ranges. It so happens that only a week or two ago we received reports of reception of both sound and vision at considerable distances. In March, May, and October of 1938 the sound was consistently received in Rhodesia, and we have also reports of reception in Baghdad and Cairo. More interesting still is the fact that on the 3rd November, 1938, the Radio Corporation of America at Riverhead, New York, reported reception of the vision signal in the form of recognizable images, accompanied, however, by shadows due to multi-path reception. Two days later they received an intelligible picture for 2 hours. The Postmaster-General's Department in Victoria, Australia, has also received the sound. In addition, the vision signal has been received in South Africa at such an intensity that it is considered that had a television receiver been available it would have been possible to interpret the signal as a picture.

We are indebted to Mr. Johnston for pointing out an error in the paper. He is correct in assuming that the master oscillator of the sound transmitter works at half the carrier frequency, and not at twice the carrier frequency. The degree of stability claimed, i.e. ± 1 part in 100 000, does obtain over a period of 24 hours, but is intended to be interpreted as obtaining over the period of a transmission. At the time the paper was compiled neither of the transmitters was crystal-controlled, but apparatus to originate the master frequency at 1/12th of the carrier frequency by crystal control has now been installed.

In reply to Dr. Grieg, we do not use a specially-built picture tube to transmit the present standard tuning caption. What happens is that the caption is drawn on a card, and a short length of film prepared from this, the film being used in a stationary position in the teleciné apparatus.

Messrs. Cooper, Wright, and Tufnail raise some interesting questions as regards television studio lighting. It has been found that any system of lighting arranged on the same lines as those employed in a theatre is unsatisfactory, in that the resulting picture has a very flat appearance. This is because television has, as it were, only one eye, and cannot of itself see the picture in three dimensions. It has long been known, in connection with the production of films, that if a system of lighting is adopted wherein the light is concentrated on the subject from the back, top, and sides, with only a minimum of diffused frontal lighting, then a useful impression of depth is secured in the picture. It is for this reason, apart from inconvenience, that footlights of the theatrical type are not used on the floor, and the bulk of the illumination is of the high-angle type. Experiments of gas discharge lamps have so far been unsatisfactory, since it is a feature of all such lamps that the light emitted depends on the instantaneous strength of the current, and when they are used with an a.c. supply this effect causes interference bands in the picture. The use of a d.c. supply for such lamps is somewhat impracticable owing to the large wastage of power which must occur in the stabilizing arrangements, and because of the bulky ancillary apparatus required.

Mr. Stevens mentions the question of synchronizing pulses *vis-à-vis* mechanical reception. It has not been necessary in this connection to make any change in the transmitted envelope form of the synchronizing signals; all that has been done is to ensure that any phase changes of the signals shall take place, if at all, very slowly instead of rapidly as was originally the case. In these circumstances, it is possible for a receiver possessing comparatively high inertia to keep itself in step.

Mr. Stollard inquires about the possibility of the extension of the range of television. No increases of power in the London Television Station have so far been contemplated, and any question of extending the service by means of additional stations is subject to future decisions to be made by the Television Advisory Committee.

The question of the necessary value of field strength for adequate reception of television, put by Mr. Hawking, is a little difficult to answer in a general way, as it depends entirely upon the strength of local interference, which may vary considerably. Experience seems to show, however, that in the absence of serious local interference, as, for example, where the receiving aerial is not situated very close to a road carrying heavy traffic, a figure of $\frac{1}{4}$–$\frac{1}{2}$ mV/m. may in general be quoted as being satisfactory, especially if an efficient directional aerial system is employed. With regard to the transmission of television signals from London to Birmingham via the coaxial cable, we are not aware that any particular technical difficulty exists.

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* *Proceedings of the Institute of Radio Engineers*, 1937, vol. 25, p. 78.

Mr. Jephcott refers to the question of the adequacy of the 3·5-Mc./sec. frequency separation between the sound and vision transmitters. Such a separation has been found in practice to be entirely adequate in view of the fact that the upper vision modulation frequency is of the order of 2·5 Mc./sec. It is thought probable that were greater power to be developed from the vision and sound transmitters, the service area of the station would be augmented in due proportion. The maximum useful range of the mobile ultra-short-wave vision transmitter is at the moment of the order of 20 miles, but it is considered possible that this may be extended by development work upon the aerial systems employed. As regards the average life expected of a cathode-ray tube, it is difficult to generalize, for much depends upon the conditions under which the tube is operated, but it may in general be said that the expected life is about the same as that of the average small receiving valve. The picture monitors used at the London Television Station develop a picture size of 10 in. × 8 in.

Messrs. A. D. Blumlein, C. O. Browne, N. E. Davis, and **E. Green** (*in reply*): In reply to Mr. Rawcliffe, allowing for the lost time between lines, his figure of 250 modulations is reduced to about 210. On the other hand, 210 complete cycles are capable of reproducing 210 black and 210 white dots giving a total of 420 dots altogether. Now, in the vertical direction at the most only 385 black and white dots can be reproduced, and this only when the dots coincide with the scanning lines. Allowing for the fact that the scanning lines may not coincide with the vertical detail, the statistical average number of black and white dots that can be resolved vertically is considerably less than 385. Hence, with 2·5 Mc./sec. an adequate horizontal detail is obtained in comparison with the vertical detail. As regards the surface of the Emitron screen, the particle size is so small that there are a large number of particles to each picture dot, so that no discernible irregularity is produced. A modulation method suitable for sound is not necessarily suitable for television, so that all practicable forms were examined, with the result stated.

In reply to Dr. Greig, pentodes of suitable rating were not available at the time the transmitter was designed. The phase displacement mentioned refers of course to the radio frequency of 45 Mc./sec. and is therefore minute when referred to the highest modulation frequency. It therefore follows that considerably more phase displacement may be tolerated, provided the condition is consistent with efficient operation of the power amplifier.

The synchronizing and vision signals are mixed by two valves having their anodes in parallel with a common anode load. Negative picture signals and positive synchronizing signals are applied to the two grids, and the mixture in the anode circuit is applied to the distribution amplifier.

In reply to Mr. Cooper, the correction for camera-cable delay is made by retarding for about 5 microseconds the triggering impulses for all pulse generating units except for the camera scanning and black-out pulses, thus relatively advancing these latter pulses. These pulses are passed through controllable delay networks to the cameras, which delay networks, together with the length of camera cable, absorb this relative advance, so correcting for the cable delay.

In deciding on the waveform to be transmitted, the shape of the synchronizing pulses were as far as possible fixed by functional considerations and not with reference to a particular receiver circuit. In general, the synchronizing signals are separated from the vision signals by a suitably biased non-linear device; and the leading edges of the signals are separated from the long frame signals by frequency selection.

In reply to Mr. Stevens, an effective " close-up " can certainly be obtained by reducing the scan, but a very great reduction of scan results in poor sensitivity and reduced resolution; further, on normal Emitrons, prolonged reduced scanning slightly marks the tube and leaves a rectangular shadow when normal scanning is resumed. The beam has not this effect on a super Emitron, which therefore allows of " electrical zooming."

The Super-Emitron has been described in a recent paper by Messrs. McGee and Lubszynski,* but it may be pointed out that it is unnecessary to have a mosaic of metal elements, as the charge can be induced on the mica surface owing to the secondary emission of the mica itself, which secondary emission is improved by the presence of caesium in the tube.

In reply to Mr. Bowler, the cable constants were originally obtained by open-circuit and short-circuit bridge measurements on short lengths, the overall losses being measured by comparison with a carefully constructed resistance attenuator.

In reply to Mr. Joseph, factors of 3 have certainly been prevalent in the number of scanning lines. For mechanical scanners, numbers like 30, 180, and 240, were convenient because the scanning discs were laid out on dividing heads marked in degrees. The number 243 which was at first used for electrical interlaced scanning was chosen as a convenient number close to 240 (then used for mechanical sequential scanning), which at the same time was an odd number made up of small factors, the small factors being convenient for electrical frequency division. The number 405 was again a convenient number close to 400 and was obtained by changing one of the factors of 243 from 3 to 5. The necessity for low factors no longer exists, as improved counters have been developed which will count comparatively large primes.

In reply to Mr. Parsons, the problem at the relay receiver was not that of preventing heterodyne interference from the main transmitter, but of preventing intermodulation effects on the first valve of the radio receiver. With the valves then available a high-frequency valve would, owing to its small feed, have been no quieter, and no less prone to intermodulation troubles than the mixer triode employed.

In reply to Mr. Tufnail, a large number of systems have been proposed which transmit a characteristic continuous signal for each picture point and do not therefore require synchronizing. It should, however, be pointed out that the more modern telegraph signalling systems are essentially "start-stop" synchronized rather than regularly synchronized. Television receivers may be made which are entirely "start-stop" synchronized, but in practice a compromise between "start-stop" and regularly-running synchronization is employed.

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* *Journal I.E.E.*, 1939, vol. 84, p. 468.

In reply to Mr. Farren, a triple interlace, having for any two successive frames not an equal upward and downward displacement of the lines, gives, according to the convention chosen, an apparent continuous upward or downward progression of the scanning lines. This apparent progression is exceedingly confusing to watch unless the picture frequency is raised to a high value, which of course makes the picture satisfactory without interlacing. With a quadruple interlace this effect is worse, unless an irregular sequence of line displacement is used, in which case, apart from the complexity of equipment, in order to obtain a satisfactory result a high picture frequency is again required so that no advantage is obtained.

In reply to Mr. Faulkner it may be stated that engineering design is primarily governed by commercial requirements. The production of high-power radio valves is no exception, and the pioneer designer exploring new applications has, initially, to accept existing technique. Power amplification with triodes at frequencies such as 45 Mc./sec., with modulation bandwidths of the order of 2·5 Mc./sec. depends upon the maintenance of a correct balance of various factors in valve design. The chief of these are: peak filament emission, anode-to-grid capacitance, current-carrying capacity of grid structure, dead-loss capacitance of anode, high d.c./a.c. conversion factor, low electron transit time.

At the present time it would appear there is no technical limit in valve design to meet immediate probable commercial power demands. The slow variations of grid-supply frequency do not give any trouble, but trouble has been experienced on mechanical receivers when the scanning frequency is made to follow very rapid phase-shifts in the power supply.

In reply to Mr. Aspin, pairs of dipoles can be made to develop their directional diagrams at very close spacings indeed, but any reduction below about a quarter-wave spacing produces a reduction in the band width of the aerial and was not therefore contemplated for television.

NORTH MIDLAND CENTRE, AT LEEDS, 17TH JANUARY, 1939*

Mr. R. J. Hines: The first question I should like to ask is in relation to the statement, made in Part I of the paper, that no practicable means was discovered of single-sideband transmission owing to the width of the band required and the necessity for transmitting down to zero frequency. I should have thought that the greater the band width to be transmitted the greater the advantage to be obtained. I can realize that the necessity for transmitting down to zero modulating frequency will make it impossible to suppress the whole of one sideband without getting rid of some of the other, but I do not quite understand why no advantage is gained by partial suppression of one sideband. Accepting, however, the necessity for full double-sideband transmission, one comes next to the question of the actual width of the bands transmitted. One gathers from the paper that the modulation frequency required for 405-line scanning is about 2·5 Mc./sec. This may be the maximum frequency which one must have to gain the full advantage of 405-line scanning, but there are present frequencies considerably in excess of that frequency. It is stated on page 774 that the modulation amplifiers are so designed that at 3·5 Mc./sec. the frequency characteristic is approximately 2 db. down. Now 3·5-Mc./sec. modulation of a carrier of 45 Mc./sec. brings us to 41·5 Mc./sec., which is the carrier for the speech, and I am not clear how interference between the vision and sound transmission is avoided.

The second question I want to put is in relation to film transmission. The television scanning is done at 25 frames per sec., and the film projector for transmitting sound film must run at 24 frames per sec. in order to give perfect reproduction of sound. How are these two requirements reconciled?

(*Communicated*) Since the presentation of the paper in Leeds I have been indebted to one of the authors for the opportunity of witnessing television, and recollection of the occasion prompts me to inquire why the film transmissions appear to be less satisfactory than those direct from the studio. Apart from the fact that the film may include pictures too full of detail or otherwise unsuitable for reproduction on a small scale, the film transmissions appeared to me to be subject to distortion which was noticeably absent from the studio transmissions. Is this because of the impracticability of applying corrections, e.g. for "tilt" and "bend," to pictures the subject matter of which is changing every few seconds?

Apart from the distortions, some of the pictures seemed to lack luminosity and contrast, the last fault I should expect to find in a film transmission, the illumination available for which should be productive, one would think, of a particularly strong signal.

Mr. W. F. Smith: It is stated on page 760 that the synchronizing signals are represented by a very low (and, very preferably, practically zero) carrier, whilst on page 766 a figure of 5 % of the peak carrier is quoted. This presumably implies approximately 100 % modulation of the carrier by the synchronizing pulses. The result of this at the receiver will be a very weak radio signal, necessitating the employment of a very sensitive receiver to detect the synchronizing signal. The receiver must also be capable of handling a very high signal strength corresponding to the "white" transmission. To attain fidelity of reproduction over such extremes in volume seems to present considerable difficulty in receiver design.

Regarding the nature of the illumination employed in the film projector, it is stated by the authors that the mosaic is exposed to the film only during the interval between successive frames of the television scanning (a period of only 0·001 sec.) and that two exposures of the film are made in this period. This implies an extremely narrow slit in the shutter and consequently little effective lighting on the mosaic. Is any special illumination employed?

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* Only the paper by Messrs. A. D. Blumlein, C. O. Browne, N. E. Davis, and E. Green ("The Marconi–E.M.I. Television System"), was read at this meeting.

In regard to the cooling of the transmitter valves, it is noted that water is employed as the cooling agent. Presumably distilled water is employed in a closed circulating system, this in turn being cooled either by air or by immersion of a portion of the circulating system in ordinary water from the public supply. Since small capacitances assume considerable importance at very high frequencies, it would seem important to keep the capacitance to the very lowest possible limit. I should like to know whether any experiment has been carried out utilizing oil as the cooling agent. This appears to provide a means of keeping the capacitance down, since oil has a lower specific inductive capacity than water.

External interference to television receivers is likely to be experienced chiefly from such sources as motor-car ignition systems and electromedical apparatus. Both these sources give rise to high frequencies near the television band and, in effect, act exactly like short-wave transmitters.

As regards motor-car ignition interference, some tests made by the Post Office as long ago as 1931 showed that a peak of interference occurred at about 17 Mc./sec., the interference falling off fairly rapidly on either side of this frequency. The tests were not extended beyond about 20 Mc./sec., where the interference was approximately 2·5 db. below that at 17 Mc./sec. This peak interference was approximately 1 μV per metre at 15 yd. from the source. It is unlikely, therefore, that interference from motor-car ignition will be experienced over a wide area. It will be confined mostly to receivers near the main roads. What is the authors' experience of this interference with television programmes?

The presence of such interference, even though it be small, may have an important effect, in view of the low level of synchronizing signal previously referred to.

Other interfering apparatus, such as electric motors, is unlikely to produce interference with the actual received signals, but the mains-borne component of interference may affect the picture by upsetting the electrostatic and electromagnetic fields upon which the action of the cathode-ray tube depends. Complete screening of the cathode-ray tube seems, therefore, to be necessary.

In view of the interest in the question of relaying television programmes to the provinces, I should be glad to know whether a split-band method of transmission over cable pairs is feasible. The feature I have in mind is the splitting of the television band into a suitable number of components, each being converted to a band of frequencies which is capable of transmission over the cable. This will result in a number of frequency bands (say, each up to 120 000 cycles per sec.) each conveyed over one pair of a carrier-telephony type of cable. Twenty such pairs would seem to be sufficient to carry the television intelligence of one transmission.

Mr. R. T. A. Dennison: My first point is in connection with the synchronizing impulses. There are two types of pulses provided—one for indicating the termination of each line and the other for indicating the termination of each frame. In the television receiver two pulses are provided for control of the line and frame scanning, and I understand that the pulses provided by the transmission are simply to ensure that the receiver pulses are triggered off at the right moment at the end of the line or frame. If the pulses in the receiver can be relied upon, it seems to me that one of the transmitted pulses, say the line pulse, can be done away with and economies effected in the cost of the television receiver and, possibly, in the transmitting equipment. In this connection I would point out that mechanical receivers have a machine which drives the scanning device. Being mains-driven, it should provide the correct line frequency, and the transmitter pulse could then be used solely to check groups of lines, i.e. each frame.

My second point is in connection with mechanical receivers, which I understand are coming on to the market now. When the television transmitter was first installed at Alexandra Palace the cathode-ray type of receiver was the only kind which gave good high-definition results, and when the mechanical type of high-definition receiver was introduced some modifications were necessary, I believe, at the transmitter. I should be interested to know whether the transmitter is now able to provide all the pulses and signals which may be required for the control of television receivers. If so, then the design of television receivers will be simplified and more scope afforded to the manufacturers.

A final point is in connection with the size of the receiver screen. I have seen demonstrations of both large- and small-screen receivers and have been impressed with them; but in watching studio broadcasts it is very noticeable on large television screens that when the head and shoulders of the subject is televised, or when the studio is occupied by one or two artists only, a large amount of space exists which could advantageously be filled in with more people or some scenery. Is this due to some restriction in the size of the studio available, or has it something to do with the angle of vision of the lens used in the television camera?

Messrs. A. D. Blumlein, C. O. Browne, N. E. Davis, and **E. Green** (*in reply*): In reply to Mr. Hines's observations on single-sideband working, no satisfactory method of single-sideband transmission had been developed at the time the Marconi-E.M.I. transmitting equipment for Alexandra Palace was contemplated. We felt justified, therefore, in refraining from the inclusion of a method of transmission which might complicate the issue in a station which was to give pioneer service. With full double-sideband transmission the selection of a sound carrier separated by only 3·5 Mc./sec. from the vision carrier was criticized, but in practice the amount of energy transmitted in the vision signals 3·5 Mc./sec. from the carrier frequency has been found to produce negligible interference in the sound channel.

In regard to film transmission, with intermittent projectors as described, the film is run at 25 frames per sec. although the film is recorded at 24 frames per sec.; the difference introduced being almost negligible in respect of both vision and sound. Since the paper was written, however, film transmitters of the continuous-motion type have been installed which may, of course, be run at any required speed irrespective of the frame frequency.

The rapidly changing character of film pictures does introduce some difficulty into the "tilt" and "bend" adjustments, inadequately illuminated scenes giving rise to unsatisfactory television images. But a greater difficulty arises in that films are printed with a gamma value considerably greater than unity. Effectively, an increase of gamma is usually introduced by the receiver characteristic, which provides a satisfactory picture from actual scenes but is over-contrasted when the picture originates from film which has been printed with a high contrast.

In connection with Mr. Smith's remarks, it will be understood, of course, that the commencement of a synchronizing signal is represented by a change of carrier from 30 % of peak to substantially zero; the receiver therefore does not need to be very sensitive to detect the synchronizing signal.

The source of illumination used in each intermittent film transmitter consists of a 30-volt 30-amp. projection-type lamp. In the interests of light efficiency, the optical system is so arranged that the shutter interrupts the light at a position where the beam has a very small cross-section.

Oil has largely been used as a cooling fluid in commercial short-wave transmitters. Its advantages of low specific inductive capacity and high resistivity are, however, offset by its low thermal conductivity, the attendant fire risk, and its cost. In the transmitter under discussion,* unwanted additional anode capacitance and losses are avoided by the insulated inlet and outlet of the water cooling-system being positioned in the assembly at a point of zero or almost zero high-frequency potential.

We have made no extensive tests on the distribution of interference over the ultra-short-wave frequency spectrum. Under average conditions about $500\,\mu V$ (peak) is required to operate a television receiver satisfactorily, so that very local motor-car interference only is likely to prove objectionable. It is frequently necessary, however, to erect a simple directional aerial to improve the receiving conditions in circumstances of poor field strength in comparison with local interference.

No consideration has been paid to any split-band method of transmission of television signals over cables, such as Mr. Smith suggests, but it is improbable that the method would offer any advantages over systems of cable transmission which have already been worked out, especially in view of the complexities which would be introduced when the attempt was made to re-assemble the signals from the various channels.

Mr. Dennison's observations on the necessity of synchronizing signals in the case of a uniformly-running scanning system, are adequately met by Section (5) of Part I of the paper. The mechanical generator for the master frequency signals described in Section (6) of Part II produces satisfactory signals for mechanical receivers, but since the paper was written this machine has been replaced by an electrical generator giving signals which also meet the requirements of mechanical reception.

The size of the studio is of course very limited for some productions, and this may account to some extent for an absence of background in the pictures. In view of the limited depth of focus of the standard cameras, however, it is considered that the producers do well to omit irrelevant detail.

WESTERN CENTRE, AT NEWPORT, 13TH MARCH, 1939†

Mr. J. V. Lugg: I understand that when it was decided to provide coaxial cables, between London and certain other large centres in England, two of the conductors were intended for the distribution of television signals. Can the author give details of any tests which may have been carried out in this connection, and also state the results of these tests?

Mr. W. Roberts: I notice that the picture is scanned completely in $\frac{1}{25}$ sec. Has this time been constant from the first, or has it been arrived at by a process of trial and error? In other words, what is the maximum retentive time of the human eye?

Could not the blind spot which occurs during scanning, when the camera has to go back from right to left without doing any useful work, have been avoided by a continuous process of scanning from left to right and then right to left? It seems to me that this would save time and avoid the mechanism having to travel backwards.

Mr. G. G. E. Lewis: The operation of the Emitron camera is dependent upon the photo-emissive nature of the mosaic and the property of the scanning beam whereby it is able to restore electrical equilibrium to the individual globules of silver which constitute the mosaic. It would be of interest to know what happens to the free electrons released by the lighter portions of the image.

I gather that in the system of outside broadcasts used by the B.B.C. the transmission from the mobile unit is effected by a radio link; are there any differences, such as depth of modulation, frequency of synchronizing pulses, and other characteristics, between the radio-link signal and the signal radiated from Alexandra Palace? My object in putting this question is to learn whether viewers of television might receive the actual signal from the mobile unit if suitably placed in its beam.

Mr. D. E. Blake: It appears that other countries have adopted different standards from that prevailing in this country so far as the number of lines is concerned. I should be glad to know whether these different figures have any mathematical significance, apart from the fact that an odd number of lines is adopted to simplify the attainment of interlaced scanning.

To the viewer, only one thing matters and that is the picture he is looking at—its size and its definition. I feel that, when the novelty has worn off, viewing for any length of time may become somewhat trying with the present sizes of picture, and particularly when a number of people are interested at the same time. Is there any scope for the development, for home use, of the methods employed in cinemas where the pictures are projected on to a screen?

Regarding the televising of plays, I have read that sometimes it is an advantage to film the play first, as this allows of editing, as in ordinary films, with a consequently better artistic result. True though this may be, I feel that it would defeat largely one of the main attractions of television, namely that the viewer is viewing the artists at the same time as they are performing. This gives a sense of intimacy, such as one experiences in a theatre, which adds greatly to the entertainment value and compensates considerably for any deficiency in the picture. There will, of course, be many instances where films will give first-class entertainment, but I think that, generally, the televising of films, however good, should form a comparatively small part of television programmes.

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* See vol. 83, p. 785.

† Joint meeting with the Institution of Post Office Electrical Engineers. Only the paper by Messrs. T. C. MACNAMARA and D. C. BIRKINSHAW ("The London Television Service") was read at this meeting.

Mr. E. S. Loosemore: Are the standards of definition, namely that a television picture should not be inferior to a standard of 240 lines per picture and 25 pictures per second, nominal or effective? If they are nominal the time occupied by line and frame flybacks and by black edging would reduce appreciably the number of lines per picture.

The construction of the Emitron and of the Super-Emitron is such that, in operation, the angle of incidence of the electron beam on the photo-electric mosaic varies considerably. What arrangements are made to maintain the beam focused on the mosaic?

Mr. C. A. Beer: The author states that a ratio of carrier frequency to modulating frequency of the order of 20 to 1 is desired. I should be glad to know whether a lower carrier frequency is impracticable, bearing in mind the problems of amplifier design and possible interference between side-bands. In carrier telephone circuits, the lower ratio is often used.

Is it to be inferred, in accordance with Fig. 19 and other references in the text, that the limiting commercial range of operation is 150 km., or can the transmitted power be considerably increased?

In a complete set of studio equipment with its apparent complexity, there is a very large number of valves and the failure of one during critical operations may be relatively serious. Is this problem catered for substantially by the provision of two or more units in the studio while valve replacements and adjustments are being made? It is the practice in this country on more recent Post Office high-frequency carrier systems where this feature arises, to arrange an automatic change-over from a main to a reserve amplifier.

Messrs. T. C. Macnamara and **D. C. Birkinshaw** (*in reply*): Mr. Lugg refers to the coaxial cable between London and provincial centres. A considerable amount of work has been done by the General Post Office on this cable; the question of the publication of the results is, of course, a matter for that authority.

Mr. Lewis asks about the modulation and other characteristics of the radio signal as transmitted by the mobile outside-broadcast transmitter. The signals are entirely the same as those radiated from the Alexandra Palace, except that for certain technical reasons the picture-signal/sychronizing-signal ratio is somewhat less. It would certainly be possible for viewers to receive the actual mobile-transmitter signal if suitably placed in its beam, but such a course would not present much advantage, as it automatically follows that they would be in a region of high field-strength from the Alexandra Palace and the main transmission would provide a more suitable signal. The latter signal also contains captions and other continuity material inserted at Alexandra Palace.

Mr. Blake mentions the possibility of filming a play and then televising the subsequent film. This procedure is not felt to be entirely desirable as, in addition to the extra cost involved, the psychological effect of knowing that the transmission is instantaneous is considered to be important. In any case, it is doubtful whether the improvement in the performance due to editing would be sufficient to justify the cost of initially preparing a film of the play.

The important aspect of valve failure is raised by Mr. Beer. As he states, there is a very large number of valves in the studio equipment, but in general the problem is catered for, as he suggests, by the provision of spare units in the studio, so that it is unlikely that valve failure will interfere more than momentarily with the transmission. Any change-over to spare apparatus is made manually, as, owing to the fact that operators must be continually at hand during a transmission, automatic features are scarcely necessary.

THE REPRESENTATION AND COMPUTATION OF FLUCTUATION VOLTAGES[*]

By F. C. WILLIAMS, **D.Phil.**, D.Sc., Graduate.[†]

(*Paper first received* 26*th January*, 1938, *and in revised form* 12*th January*, 1939.)

SUMMARY

Much has been written concerning the fundamental physics of fluctuation phenomena, but the methods to be used in computing signal/noise ratio in the complex circuits of modern communication engineering have never been fully described. This paper gives particulars of two methods by which such computations can be made by the ordinary processes of circuit analysis, no reference to the obscure physical mechanism of the effects being necessary.

In the first method, voltage representation, the fluctuations associated with valves and resistances are represented by generators injecting voltages of specified mean-square value in series with each valve or resistance. In the second method, current representation, the representation is by a current injected by a hypothetical generator, having infinite internal impedance, connected in parallel with the valve or resistance.

Either method may be used, and their relative values in given circumstances are discussed.

Both representations appear devoid of physical significance and neither has been rigorously justified theoretically, but extensive experiments have shown that exact calculations of fluctuations in complex networks can be made by their use.

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(1) Introduction.
(2) Voltage Representation of Thermal Fluctuations.
(3) Voltage Representation applied to Thermionic Valves.
(4) Current Representation of Thermal Fluctuations.
(5) Current Representation in Complex Networks.
(6) Current Representation applied to Thermionic Valves.
(7) Physical Discussion.
(8) Conclusions and Acknowledgment.
Bibliography.
Appendices.

(1) INTRODUCTION

It has long been known that there is a spontaneous oscillating potential difference between the ends of an isolated resistance: it is believed to be due to thermal agitation of the free electrons and has a mean-square value which is proportional to the resistance and to its absolute temperature. This oscillation is augmented if the resistance carries a current which has passed through a thermionic valve. The two components of oscillation are often called respectively thermal and thermionic fluctuation voltages. All electrical communications suffer from them as an inevitable background which ruins intelligibility when the strength of the signal is less than some definite amount, which is independent of subsequent amplification, which magnifies both alike. Hence it is desirable to be able to predict the fluctuation voltage inherent to any assembly of circuits and thermionic valves.

Considerable research has not yet revealed the exact mechanism of these effects, and it is laborious to estimate their probable magnitude in complex circuits. Recently, however, the author described[‡] a method of representing the phenomena by which the fluctuations generated in any specified network can be calculated by the ordinary processes of circuit analysis, the physical mechanism of the effects being ignored. Extensive experiments have vindicated such representation completely.

In this representation the distribution of potential developed along the length of a resistance is simulated, for simplicity, by a concentrated generator[§] producing a specified e.m.f. and supposed inseparable from the resistance: an analogous representation is adopted for thermionic fluctuations. Despite its physical shortcomings, such a representation is convenient technologically, since then the result rather than the mechanism is of importance: it will be termed " voltage representation."

There is an alternative, which will be termed " current representation "; its scope is no greater, but sometimes it is more convenient. This paper sets out the principles and application of both representations. Voltage representation, which has been used in other papers, is first summarized and its application extended. Since the purpose of this paper is to facilitate computation, the physical aspects of the representations will be ignored at first.

(2) VOLTAGE REPRESENTATION OF THERMAL FLUCTUATIONS

Nyquist[||] has shown that the fluctuation voltage across an isolated resistance R at temperature T (absolute) is defined by the equation

$$\overline{v^2} = 4RkTdf \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Here $\overline{v^2}$ is the mean-square value of those sinusoidal components of the total fluctuations having frequencies within the small range df, and k is the Boltzmann's constant. In complex networks at uniform temperature the fluctuation voltage between any two points B and B′ in the network is expressed by

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

[†] Electro-Technical Laboratories, Manchester University.

[‡] See Bibliography, (1) and (2).

[§] A concentrated generator is the most familiar source of e.m.f. In the present case it is, properly used, an accurate mathematical tool, but is physically inaccurate. An equal distributed e.m.f. generated along the length of the resistance would also suffice mathematically but would again be physically inadequate since the required form is $\overline{v^2} \propto R$, not $v \propto R$: the simpler representation has therefore been adopted.

[||] See Bibliography,(3).

$$\overline{v^2_{BB'}} = 4rkTdf \quad . \quad . \quad . \quad . \quad . \quad (1a)$$

where now r is the real component of the impedance measured between B and B′,* and df is supposed infinitesimally small. The fluctuation in any finite frequency range is found by integrating (1a) between the required frequency limits.

Thermal fluctuations in a large class of networks can be computed by (1a), but since Nyquist's proof is based on considerations of thermodynamic balance it gives no indication of the mechanism producing $\overline{v^2_{BB'}}$, or of the contribution to $\overline{v^2_{BB'}}$ made by particular elements of the whole network. Computations of signal/noise ratio are often tedious, and the influence of changes in the circuit parameters is difficult to assess. It applies only to networks at uniform temperature. This is perhaps not a serious limitation where thermal fluctuations alone are concerned, but when thermionic as well as thermal fluctuations are generated in a network Nyquist's equation does not suffice.

These limitations are obviated by the author's process of computation,† in which every element of resistance in the network is replaced by the equivalent circuit element shown in Fig. 1.

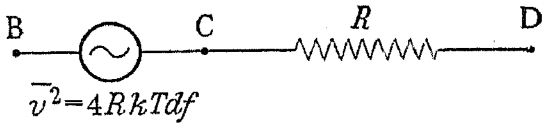

Fig. 1

Here R is an element of resistance in the network and T is its absolute temperature. The generator is supposed to maintain between B and C a p.d. of mean-square value defined by the equation

$$\overline{v^2} = 4RkTdf \quad . \quad . \quad . \quad . \quad . \quad . \quad (1b)$$

Since the generator represents an effect associated with the *whole* of R and inseparable from it, B and D alone are supposed available for external connection (i.e. in drawing out the equivalent circuit of a given network the resistance elements such as R must be so chosen that connection is made only to their extremities: a tapped resistance must be split into two or more elements). Having made these substitutions, the resistances as such are supposed devoid of thermal-agitation e.m.f.: it should be noted that analogous generators are not associated with reactive elements of the network. In order that the circuit parameters shall not be changed by the inclusion of the generators, they are supposed to have zero internal impedance.

It is shown in Appendix 1 that if in a general network there are generators in series with the arms a, b, . . . x, etc., yielding respective fluctuation voltages in the range df of mean-square values $\overline{v^2_a}, \overline{v^2_b} \ldots \overline{v^2_x}$, etc., there will result between any two points B and B′ in the network a fluctuation voltage (in the range df) of mean-square value

$$\overline{v^2_{BB'}} = Z^2_{BB'} \sum \frac{\overline{v^2_x}}{Z^2_{xB}} \quad . \quad . \quad . \quad . \quad (2)$$

where $Z_{BB'}$ is the modulus of the network impedance measured between B and B′ and Z_{xB} is the modulus of the transfer impedance from the hypothetical generator in series with the arm x to a short-circuit joining B and B′ (i.e. $1/Z_{xB}$ = the current in a link joining B and B′ per unit e.m.f. in series with the arm x).

With thermal fluctuations represented as in Fig. 1,

$$\overline{v^2_x} = 4R_xkT_xdf \ldots \text{etc.}$$

where R_x is the series resistance of the arm x and T_x is the temperature of R_x. Hence, now,

$$\overline{v^2_{BB'}} = 4kdfZ_{BB'} \sum \frac{R_xT_x}{Z^2_{xB}} \quad . \quad . \quad . \quad . \quad (3)$$

This particular form of (2) has been deduced before.*

The real component of the impedance from B to B′ is,†

$$r = Z^2_{BB'} \sum \frac{R_x}{Z^2_{xB}} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

With uniform temperature (3) reduces to (1a) (see equation 4), but the relative importance of the contribution from a given resistance element can be assessed from (3) and not from (1a). Further, (3) is often easier to apply than (1a), since terms such as Z_{xB} relate to the network short-circuited across B and B′, which often greatly simplifies the network.

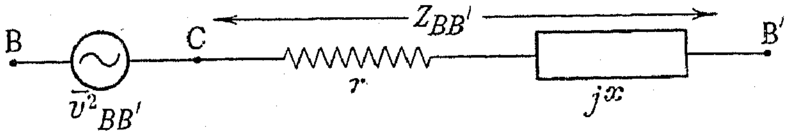

Fig. 2

Representation of thermal effects by a concentrated generator can be extended to apply to apparent as well as real resistance elements. Thus, having solved (3) for a given network, the network and its associated fluctuation can be replaced by the complex equivalent element shown in Fig. 2. Here the generator maintains between B and C a p.d. of mean-square value $\overline{v^2_{BB'}}$; with uniform temperature the relevant value is given by (1a). Figs. 1 and 2 are then equivalent, for the addition of a reactive element in Fig. 2 is irrelevant, since no part of $\overline{v^2_{BB'}}$ is to be ascribed to it. If the temperature is not uniform, Figs. 1 and 2 remain qualitatively equivalent but now $\overline{v^2_{BB'}}$ has the value given by equation (3). Again, B and B′ alone are supposed available for external connection.

Representation by Fig. 2 instead of Fig. 1 may be adopted when it is convenient to use a step-by-step method, the network being split into suitable components, each of which is reduced separately to the form typified by Fig. 2. It can be shown that this process is valid for predicting the fluctuations in the whole network.

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* Throughout this paper the impedances referred to are those relevant to sinusoidal oscillations of frequency f, the mid-frequency of df.

† See Bibliography, (1) and (2).

* See Appendix 1 of Bibliography (1).

† See Appendix 2 of Bibliography (1).

It may be noted that the representation shown in Fig. 2 is essential to the solution of problems where physically isolated resistance elements do not exist, for example in long cables.* Arms such as that shown in Fig. 2 are within the scope of (2) but not of (3).

(3) VOLTAGE REPRESENTATION APPLIED TO THERMIONIC VALVES

In general, thermionic valves may be represented diagrammatically by the equivalent circuit element shown in Fig. 3(*a*), where ρ, μ, and v_g, are respectively the anode slope resistance, the amplification factor, and the applied grid voltage. A representation suitable for fluctuation computations proposed previously† is shown in Fig. 3(*b*). Here the generator maintains between B and C a p.d. of mean-square value

$$\overline{v^2} = (g^2\overline{v_g^2} + 2AIe)\rho^2 df \quad . \quad . \quad . \quad . \quad (5)$$

where g is the mutual conductance of the valve. The second term in (5) is the contribution from shot fluctations generated in the valve;‡ the first is the contribution from the fluctuation voltage applied by any network connected to the grid.

This representation is valid only in circuits having no coupling between the anode and grid circuits. In retroactive circuits the fluctuation voltage imposed on the grid contains a component dictated by shot fluctuations of anode current; the two terms in equation (5) then have related components and their addition is inadmissible. This limitation can be avoided by using Fig. 3(*b*) to represent the valve and its inherent shot fluctuation only, the grid network being separately represented as already explained, and the contribution from its resistive elements included in the summation of equation (2). The mean-square output voltage of the generator in Fig. 3(*b*) is then

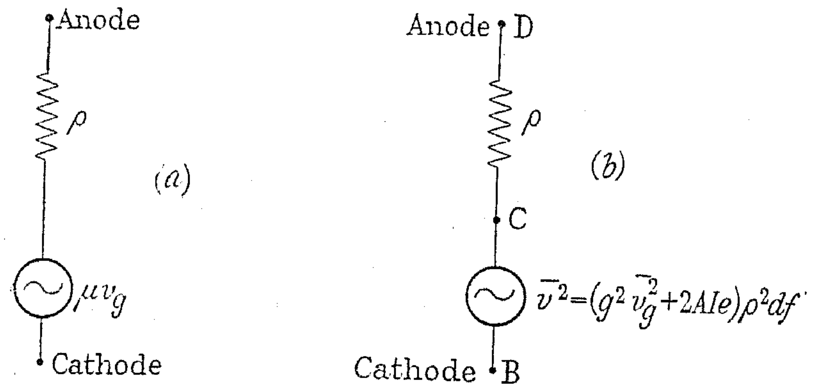

Fig. 3

$$\overline{v^2} = 2AIe\rho^2 df \quad . \quad . \quad . \quad . \quad . \quad (5a)$$

Both representations of thermionic fluctuations lie within the scope of equation (2). The first is probably more convenient in non-retroactive circuits.

Voltage representation is valid in any network which does not contain non-linear elements: the network may contain thermionic valves, provided these operate only over the linear range of their characteristics.§

(4) CURRENT REPRESENTATION OF THERMAL FLUCTUATIONS

In the preceding Sections the known thermal fluctuation voltage $\overline{v^2} = 4RkTdf$ associated with an isolated resistance was arbitrarily ascribed to a generator in series with R: alternatively it may be ascribed to a generator in parallel with R, injecting across R a current

$$\overline{i^2} = \frac{4kT}{R}df \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

This representation is shown in Fig. 4.

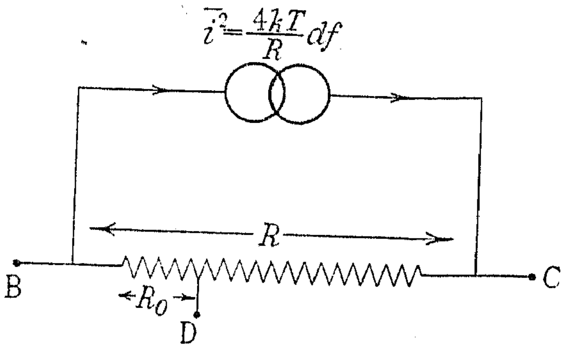

Fig. 4

It must be emphasized that $\overline{i^2}$ is not to be confused with currents actually flowing in R owing to the thermal motion of free electrons: it is a purely imaginary quantity which simulates the effect of those currents but is physically different from them (see Section 7). Again, the resistance itself is supposed free from thermal e.m.f., and B and C only are supposed available for external connection. (The representation is invalid for a tapping point such as D, for it yields $\overline{v^2_{BD}} = 4kTR_0^2df/R$ instead of $\overline{v^2_{BD}} = 4R_0kTdf$.)

In order that the circuit parameters shall be unchanged by adding these hypothetical generators they must be endowed with infinite internal resistance;* this corresponds to the zero resistance property postulated for the generators in Section (2). The generator is drawn as shown in Fig. 4 to indicate this infinite internal resistance.

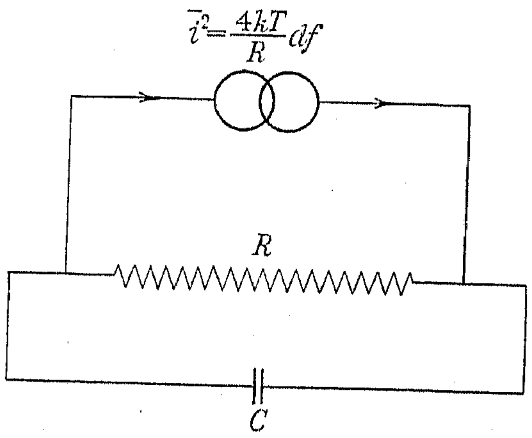

Fig. 5

In this representation it is important to remember that $\overline{i^2}$ is not confined wholely to R; part may flow through a network connecting B and C, the division of $\overline{i^2}$ between the two parts being dictated by Ohm's law.

Fig. 5 is an example of the use of current representation.

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* See Bibliography, (1).

† *Ibid.*, (2).

‡ *I* is the steady anode current, *e* the electronic charge, and *A* an arbitrary coefficient of the order of 0·2: for fuller information see Bibliography, (4).

§ D. A. Bell [see Bibliography, (5)] suggests that the process is also applicable to non-linear circuits, but appears to have overlooked the fact that in such circumstances the mean-square value of the sum of a number of fluctuation voltages, or currents, is not the sum of their mean-square values.

* It follows that the generators have an infinite induced e.m.f.; this is perhaps contrary to general experience but is not fundamentally wrong. Such generators have been used before [see Bibliography, (6)] in analysis, and the pentode valve is a close approximation to realization of such a generator.

It is required to find the total fluctuation voltage across the condenser C; the result is known to be kT/C.

The impedance of R and C in parallel is

$$R/\sqrt{[1 + R^2C^2(2\pi f)^2]},$$

hence when $\overline{i^2}$ flows through them jointly we have

$$\delta\overline{v_c^2} = \frac{4kT}{R}\, df \cdot \frac{R^2}{1 + R^2C^2(2\pi f)^2}$$

Therefore

$$\overline{v_c^2} = \int_0^\infty \delta\overline{v_c^2} = 4kTR\int_0^\infty df/[1 + R^2C^2(2\pi f)^2]$$

$$= \frac{2kT}{\pi C}\,[\text{arc tan } 2\pi RCf]_0^\infty = \frac{kT}{C}$$

In discussing one of the author's earlier papers, D. A. Bell* proposed an alternative current representation. In his reply the author gave reasons for doubting its validity, and further discussion here appears unnecessary.

(5) CURRENT REPRESENTATION IN COMPLEX NETWORKS

Appendix 2 shows that if in a general network a fluctuation current of mean-square value $\overline{i_x^2}$ (within the range df) is injected across the typical arm x, there will result between any two points B and B′ in the network a p.d. of mean-square value (within the range df)

$$\overline{v_{BB'}^2} = \Sigma N_{xB}^2\overline{i_x^2} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where N_{xB} is the modulus of the transfer impedance from a current injected across the arm x to the points B, B′ (i.e. the p.d. between B and B′ per unit current injected across the arm x) measured at the frequency f about which df is disposed.

If $\overline{i_x^2}$ represents thermal fluctuations in the shunt resistance R_x of the arm x, then

$$\overline{i_x^2} = \frac{4kT_x}{R_x}df$$

and

$$\overline{v_{BB'}^2} = 4kdf\sum\frac{N_{xB}^2T_x}{R_x} \quad . \quad . \quad . \quad . \quad (7a)$$

Appendix 3 shows that if the impedance between B and B′ is $Z_{BB'}$ having shunt components r' and jx'

$$\left[\frac{1}{Z_{BB'}} = \sqrt{\left\{\left(\frac{1}{r'}\right)^2 + \left(\frac{1}{x'}\right)^2\right\}}\right]$$

then

$$\frac{1}{r'} = \frac{1}{Z_{BB'}^2}\sum\frac{N_{Bx}^2}{R_x} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where N_{Bx} is the modulus of the transfer impedance from a current injected at B and B′ to the extremities of R_x (i.e. the p.d. across R_x per unit current injected at B and withdrawn at B′).

With linear networks, $N_{xB} = N_{Bx}$. It follows that with uniform temperature

$$\overline{v_{BB'}^2} = \frac{4kTdf}{r'}Z_{BB'}^2 \quad . \quad . \quad . \quad . \quad . \quad (1c)$$

which fluctuation voltage would result if the only fluctuation current present were

$$\overline{i_{BB'}^2} = \frac{4kTdf}{r'} \quad . \quad . \quad . \quad . \quad . \quad (6a)$$

flowing through the impedance $Z_{BB'}$. This representation of the whole network is shown in Fig. 6. Such representation can be proved valid whether the network is isolated or not, provided B and B′ alone are supposed available for external connection, and provided $\overline{i_{BB'}^2}$ may flow partly through any external network connecting B and B′. Fig. 6 corresponds to Fig. 2, and is consistent with the representation for a simple resistance shown in Fig. 4.

A representation similar to Fig. 6 can be adopted when the temperature is not uniform, but then the relevant value of $\overline{i_{BB'}^2}$ is $\overline{v_{BB'}^2}/Z_{BB'}^2$, or, from (7a),

$$\overline{i_{BB'}^2} = \frac{4kdf}{Z_{BB'}^2}\sum\frac{N_{xB}^2T_x}{R_x} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

Such representation lies within the scope of (7) but not of (7a).

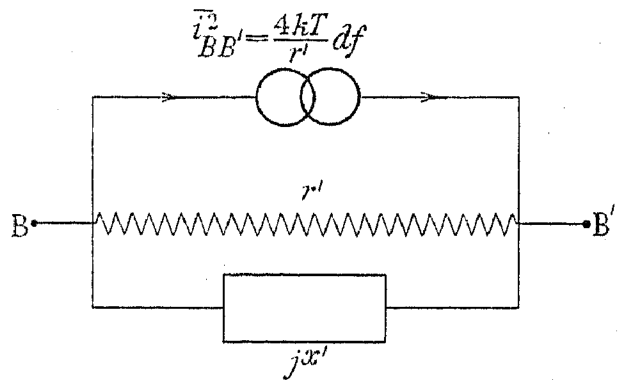

Fig. 6

The equivalence of current and voltage representations is easily proved, for it can be shown that in a linear network*

$$N_{Bx} = \frac{R_xZ_{BB'}}{Z_{Bx}};$$

equations (7a) and (3) are therefore equivalent.

It is permissible to combine voltage representation with a shunt form of $Z_{BB'}$, or current representation with a series form of $Z_{BB'}$; these forms are straightforward variations of those given, but appear to be of little value.

(6) CURRENT REPRESENTATION APPLIED TO THERMIONIC VALVES

Although the circuit shown in Fig. 3(*a*) is the better-known representation of a valve in circuit analysis, that shown in Fig. 7(*a*) is often preferable.†

Here the effect of applied grid voltage is represented by a generator of infinite impedance supplying a current gv_g as shown. Fig. 7(*b*) is a suitable representation of a valve, and its inherent fluctuation together with any fluctuations

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* See Bibliography, (5).

* Note: in deriving this result it is necessary to regard the arm x as a pure resistance R_x in each case: this in no way limits the generality of the result since fluctuations are not to be ascribed to reactive elements in the network.

† See Bibliography, (6).

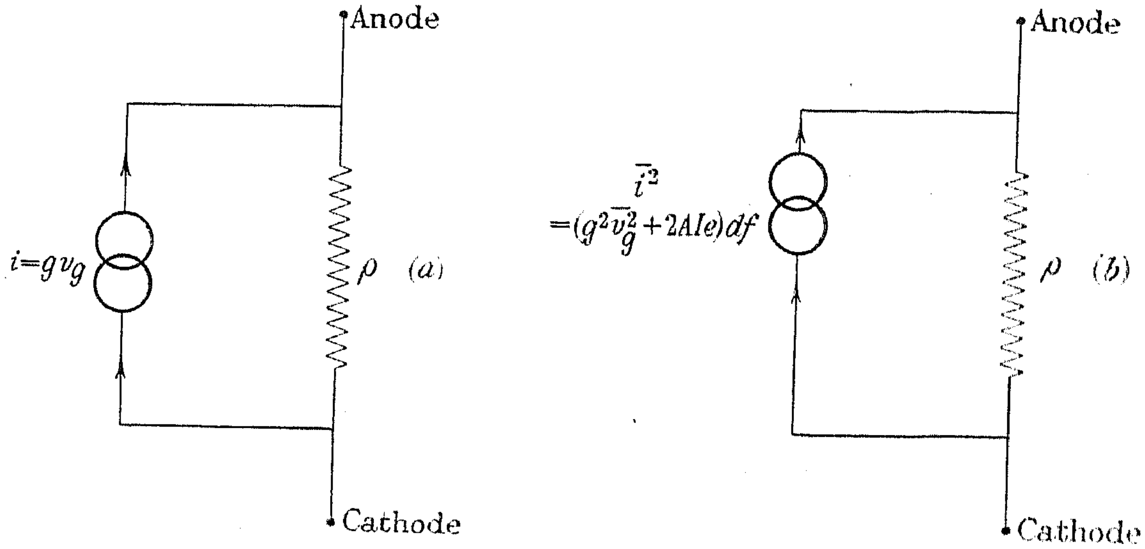

Fig. 7

generated by a network connected to its grid; it corresponds to Fig. 3(*b*) in terms of voltage representation. As before, the same figure can be used to represent fluctuations inherent to the valve only by putting $\overline{v_g^2}df = 0$, contributions from network elements in the grid circuit being then separately assessed and included in the summation of (7). Again the first representation applies only to non-retroactive circuits, and both lie within the scope of (7). The validity of these representations depends solely on experimental checks of computations based on their use.

To calculate the fluctuation voltage developed across the load impedance of a diode valve (see Fig. 8) we proceed as follows: First replace the impedance $Z_{CC'}$ by its equivalent shunt components; with uniform temperature the resulting equivalent circuit is shown in Fig. 9. With non-uniform temperature $\overline{i_{r'}^2}$ may be derived from (9).

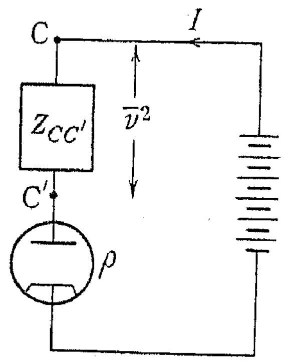

Fig. 8

Since the mean-square value of the sum of two fluctuation currents is the sum of their mean-square values, it follows by inspection that

$$\overline{v^2}=Z^2\left(\frac{4kT}{r'}+2AIe\right)df \quad . \quad . \quad . \quad (10)$$

where
$$\frac{1}{Z^2}=\left(\frac{1}{r'}+\frac{1}{\rho}\right)^2+\left(\frac{1}{x'}\right)^2$$

[In more complex cases the necessary summation can be made with the help of (7).]

When $jx' = \infty$ and $r' = R$, equation (10) becomes

$$\overline{v^2}=\left(\frac{R\rho}{R+\rho}\right)^2\left(\frac{4kT}{R}+2AeI\right)df \quad . \quad . \quad (11)$$

This equation has been derived before* but the accompanying discussion was inadequate; it is very important and has been completely verified experimentally.†

If a triode replaces the diode, a network connected in its grid circuit is best represented by means of Fig. 2, which permits ready evaluation of $\overline{v_g^2}df$. It then follows from Fig. 7(*b*) and the process above that

$$\overline{v^2}=Z^2\left(\frac{4kT}{r'}+2AIe+g^2\overline{v_g^2}\right)df \quad . \quad . \quad (12)$$

Equations (10), (11), and (12), can also be derived by voltage representation, but then the result is not obvious by inspection of the figure corresponding to Fig. 9, and appeal to (2) is necessary. Thus current representation is preferable where circuit elements connected in parallel are concerned, voltage representation being preferable with series-connected elements. It is recommended that voltage representation be used when both series and parallel combinations are present, for the analysis then follows more closely the ordinary processes of circuit algebra.

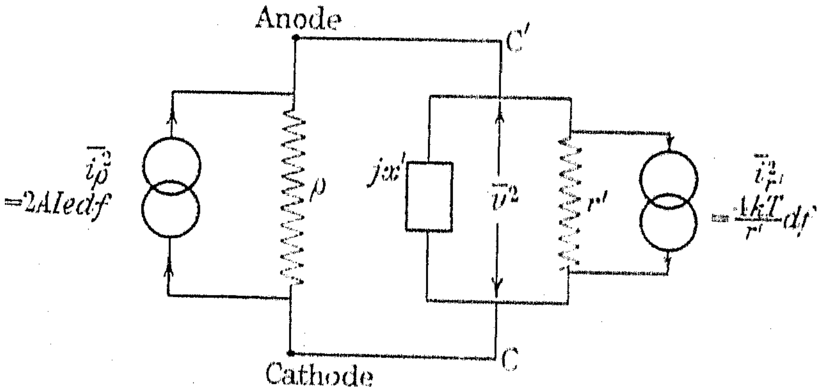

Fig. 9

Thermionic fluctuations have been expressed in terms of "shot effect"; the author prefers this method since it readily includes flicker effect, ionization, etc., and is technologically convenient.

Other workers‡ prefer a thermal interpretation and ascribe to ρ a thermal fluctuation corresponding to some temperature T_F whose value depends very greatly on the operating conditions of the valve. The representations apply equally well to such interpretation, the relevant injected currents or e.m.f.'s being derived from the identity

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* See Bibliography, (4).

† *Ibid.*, (2).

‡ *Ibid.*, (7) and (5)

$$2AIe = \frac{4kT_F}{\rho} \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Some further indication of the great value of these arbitrary representations may be derived from consideration of equation (11): this basic equation, relating to coexistent thermal and thermionic fluctuations, is easily derived by their use, yet it is scarcely possible to derive it by logical argument from the physical phenomena involved.

(7) PHYSICAL DISCUSSION

It has been suggested that, of the two representations, the "current" has the greater physical significance; yet it is difficult to reconcile either with the few known physical facts. It seems impossible to visualize any manner in which an e.m.f., in the ordinary sense, can be generated in an isolated resistance. At first sight the current representation appears more hopeful, for current corresponds to motion of the electrons, and such motion must arise from thermal agitation. However, a current which fully explained the fluctuations would not have a uniform value throughout the length of the resistance. For in an isolated resistance R the current must always be zero at the extremities: further, if a tapping be taken which encloses a resistance R_0 from one end (see Fig. 4) the current traversing R_0 must have a mean-square value $4kT/R_0 . df$, since the mean-square voltage across R_0 is to be $4R_0kTdf$. Hence the "thermal current" traversing the section R_0 depends on the value of R_0, a condition which cannot exist with currents as normally visualized. It is for these reasons that it is necessary to postulate connection only at the ends of the resistance elements when the arbitrary representations described above are used, and it seems evident that the current $4kT_xdf/R_x$ as here defined is devoid of physical significance; it bears no exact relation to currents that may actually flow in the resistance owing to thermal motion of the free electrons.

The impossibility of defining the actual current in R perhaps indicates a fundamental difference between shot and thermal effects, for the fluctuation current traversing a valve is the same at all cross-sections of the anode-cathode path for all frequency components whose periodic time is appreciably greater than the transit time. Current representation may not be entirely devoid of physical significance when applied to thermionic valves.

(8) CONCLUSIONS AND ACKNOWLEDGMENT

It is concluded that current and voltage representation are tools by which fluctuation voltages can be accurately calculated. Either representation may be used, but in general voltage representation is preferable since the analysis is more in keeping with ordinary circuit algebra. Current representation is more convenient when circuit elements connected in parallel alone are concerned, and perhaps has some physical significance when applied to thermionic fluctuations.

With current representation it is vitally important to remember that equations (6), (6a), and (9), relate to currents supplied to the resistance by shunt generators of infinite internal impedance, and not to currents actually flowing wholely in the resistance.

The formulae relating to complex networks hold only if the networks respond linearly to the fluctuations: in non-linear networks the addition of mean-square values is not permissible. In non-linear networks it is not known whether the basic representations of Figs. 1 and 4 remain valid or whether Nyquist's equation (1*a*) for the whole network still holds. The derivation of equation (3) suggests that one or the other is then at fault.

The author is indebted to Mr. E. B. Moullin, M.A., Member, for much helpful discussion.

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APPENDIX 1

Fig. 10 represents a general network, the typical arm "x" and the points B and B′ alone being shown in detail.

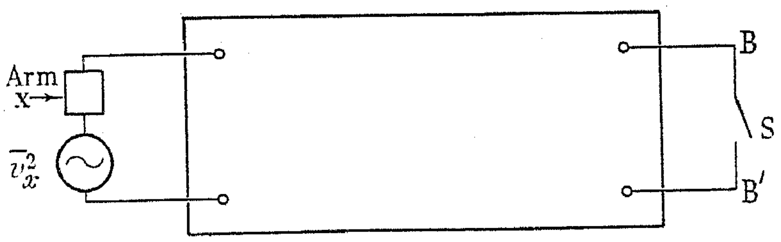

Fig. 10

If the switch S is closed $\overline{v_x^2}$ will drive through it a current of mean-square value

$$\frac{\overline{v_x^2}}{Z_{xB}^2} \text{ (Symbols as defined in the text)}$$

Generators in the remaining arms will drive similar component currents, which will be totally unrelated to each other provided the network is linear. Hence the mean-square value of the total current through the switch is

$$\sum \frac{\overline{v_x^2}}{Z_{xB}^2}$$

If this current is interrupted by opening the switch it follows from the inverse of Thévenin's theorem that there will appear between B and B′ a p.d. of mean-square value

$$\overline{v_{BB'}^2} = Z_{BB'}^2 \sum \frac{\overline{v_x^2}}{Z_{xB}^2} \quad \text{(equation 2 of text)}$$

[The argument is given in greater detail in Appendix 1 of Bibliography (1), where a particular case is considered.]

APPENDIX 2

Fig. 11 represents any complex network, the typical arm x and the points BB′ alone being shown in detail. With the definition of N_{xB} given in the text it follows that the fluctuation voltage between B and B′ due to the current $\overline{i_x^2}$ is

$$\overline{v_x^2} = N_{xB}^2\overline{i_x^2}$$

Any other injected current will yield a similar fluctuation voltage which will be totally unrelated to the first, provided the network is linear. Hence the total fluctuation voltage between B and B′ is the sum of all such terms as $\overline{v_x^2}$ and is defined by the equation

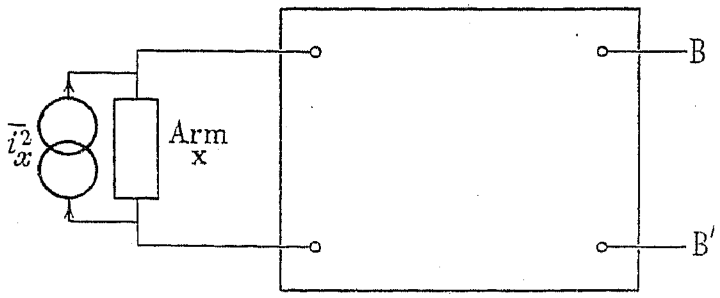

Fig. 11

$$\overline{v^2}_{BB'} = \Sigma\overline{v_x^2} = \Sigma N_{xB}^2\overline{i_x^2} \text{ . . . (equation 7 of text)}$$

APPENDIX 3

If in the network of Appendix 2 all fluctuation currents such as $\overline{i_x^2}$ are removed and a sinusoidal e.m.f. of r.m.s. value E and frequency f is applied across B and B′, a current

$$I = \frac{E}{Z_{BB'}}$$

will enter the network, where $Z_{BB'}$ is the network impedance from B to B′. There will result a potential E_x across the arm x such that

$$E_x = N_{Bx}I = \frac{N_{Bx}E}{Z_{BB'}}$$

where N_{Bx} is the transfer impedance from a current injected at BB′ to the extremities of the arm x; it is equal to N_{xB} if the network is linear. The power dissipated in the arm x is

$$P_x = \frac{E_x^2}{R_x} = \frac{E^2}{Z_{BB'}^2}\cdot\frac{N_{Bx}^2}{R_x}.$$

where R_x is the shunt resistance of the arm x.

The total power dissipation is

$$P = \Sigma P_x = \frac{E^2}{Z_{BB'}^2}\sum\frac{N_{Bx}^2}{R_x}$$

Alternatively, P can be expressed in terms of E and the shunt components r' and x' of $Z_{BB'}$, such that

$$\frac{1}{Z_{BB'}} = \frac{1}{r'} + j\frac{1}{x'}$$

i.e.

$$P = \frac{E^2}{r'}$$

whence

$$\frac{1}{r'} = \frac{1}{Z_{BB'}^2}\sum\frac{N_{Bx}^2}{R_x} \text{ . . . (equation 8 of text)}$$

ELECTRICITY SUPPLY TARIFFS AND CHARGES*

By J. A. SUMNER, Member.†

CONTENTS

(1) Statutory and Administrative Developments in Relation to Tariffs.
(2) Trend of Tariff Structure and Charges.
(3) General Tendencies of Costs and Charges.
(4) Developments in Domestic Tariffs.
(5) Developments in Industrial Tariffs.
(6) Summary of Progress.

(1) STATUTORY AND ADMINISTRATIVE DEVELOPMENTS IN RELATION TO TARIFFS

1930 Report on "Uniformity of Electricity Tariffs and Charges"

In 1930 the report of the Committee appointed by the Electricity Commissioners to consider tariffs and charges‡ became available. The Terms of Reference of this Committee were "To consider the various kinds of charges and tariffs offered by authorized undertakers in connection with the supply of electricity for lighting, domestic, office, and power purposes, and to make definite proposals whereby a greater measure of uniformity in respect of charges and tariffs could be brought about in the electricity supply industry." The Report emphasized the advantage to all supply undertakings and their consumers of a "standard multi-part tariff for general domestic supplies," and it would appear that in 1930 many supply undertakings were not offering a tariff of this nature. Important sections of the Report are those which relate to the statutory position of an undertaking which proposed to offer a multi-part tariff, to "the complexity of the provisions relating to statutory and non-statutory tariffs," and to the essential differences which are indicated between these two classes of tariffs.

The reader is referred to the actual Report for more complete details of the Committee's recommendations, but the findings of the Committee may be summarized as follows:—

(1) That it is to the advantage of supply undertakings and consumers that a standard multi-part tariff should be offered for general domestic supplies.

(2) That since the minimum quarterly charge is an integral part of the fixed charge of a multi-part tariff, a minimum quarterly charge should be enforced on consumers on the flat rate.

(3) That the present multiplicity of tariffs should cease; the "size-of-house" tariff is recommended as the most suitable for adoption for supplies to domestic premises and this type of tariff is recommended as the *statutory* multi-part tariff for such supplies. It is also recommended that the secondary or unit charge should be uniform in a particular area of supply.

(4) That for business or office premises the statutory tariff should be a multi-part tariff with the fixed charge based upon the kilowatts of installed demand, and for small industrial supplies a fixed-charge basis of combined consumption and installed demand; for rural areas the tariff is not specified but it is recommended that it should be one which will "Promote the uses of electricity for all purposes as quickly as possible."

In view of the complexity of the tariff problem it was hardly to be expected that there would be general agreement with the above recommendations, but it does not seem, during the eight years that have elapsed since the Report was published, that the size-of-house tariff has received enough support to justify the stamp of official approval being given to it as the statutory tariff for all supply undertakings. The general tendency in the change of tariff structure may be judged from Table 1.

Report of the McGowan Committee

The publication in 1936 of the Report of the McGowan Committee appointed to consider the reorganization of electricity undertakings is an important event which has occurred during the period under review; the future influence of this Report upon tariffs and charges is likely to be far-reaching. The Committee stated that "An important factor in securing such an improvement, i.e. of demand in a supply area, will be the adoption of uniform methods of charge throughout the consolidated area and as far as possible actual uniformity of charges. . . . It should be the objective of a consolidated undertaking to bring about uniformity of tariffs as soon as possible. . . ."

In general, the Report emphasized the importance of suitable tariffs and charges as an influence upon increased consumption, and stressed the need for a greater uniformity of tariffs and charges.

F.B.I. Report on Tariffs

A further event in connection with tariffs which has occurred during the period under review is the publication of the Report of the Tariffs Sub-Committee of the Federation of British Industries. This Sub-Committee reported on the possibility of ". . . obtaining greater uniformity in the technical basis of two-part tariffs, as used in connection with the supply of electrical energy for industrial use"; they were not able, under their terms of reference, to report on the actual monetary charges made by supply undertakings for power supply, and the investigation is therefore confined to the actual tariffs, i.e. the bases of charge. The Sub-Committee suggested, *inter alia*, that where electrical energy is purchased for ordinary industrial purposes on a two-part tariff:—

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* A review of progress, covering the period 1930–1938.

† West Midlands Joint Electricity Authority.

‡ Report on "Uniformity of Electricity Tariffs and Charges" (H.M. Stationery Office, 1930).

(1) The period of integration of maximum demand should be 30 minutes.

(2) Power-factor adjustment should be applied automatically by measuring the maximum demand in kVA.

(3) There should be a uniform charge for both power and lighting in industrial premises, provided the installed capacity of the lighting did not exceed 20 per cent of the capacity of the whole installation.

(4) The agreed basis of charge for industrial supplies should only apply to installations of not less than 50 kVA, or having an annual consumption of at least 50 000 kWh.

(5) There should be a coal price adjustment to the charge, in accordance with the C.E.B. scales for separate areas, but increased by 10 per cent.

Uniformity in Tariffs and Charges

The need for a greater uniformity in tariffs is one of the features which is predominant in the three Reports already referred to. Reference has also been made to this question in the Annual Reports of the Electricity Commissioners and in recent discussions before The Institution.

The discussions at the Institution Centres indicated that a majority of the speakers do not consider that uniformity, *per se*, will increase to any great extent the rate of increase in consumption, but that this increase will be brought about more fully by a wider sales development policy and by the supply undertakings extending facilities to provide cheaper consumer apparatus. The suggestion was made that the supply undertakings should invest money in consumers' apparatus and consider the consumers' installation as part of the normal distribution system.

It is difficult, however, to see how the supply undertakings can avoid ultimately a much closer consideration of this important question of unification, in view of the pressure that consumers are likely to exert in the near future, due to the many anomalies which exist in tariffs and charges for electricity.

During the past seven years there has been an increasingly large number of undertakings which have adopted a two-part domestic tariff with a secondary charge of ½d. per kWh and, as the average consumption per consumer increases, the proportion of the total revenue which is derived from primary charges will decrease, thereby making more favourable the conditions for a material standardization of tariffs and charges.

(2) TREND OF TARIFF STRUCTURE AND CHARGES

It is not possible to make a complete analysis of tariff rates and of the number of consumers taking supply at different charges or on the different classes of tariffs, owing to the lack of available information. In 1934, however, the Electricity Commissioners published data* which afforded some indication of the manner in which tariffs and charges were distributed.

The Report showed that at the end of 1934 two-part tariffs for domestic supplies were being offered by 506 undertakings, or 81 per cent. The secondary charge of these two-part tariffs ranged from over 1d. per unit to ½d. or less. The fixed or service charge of the tariffs was on a variety of bases, the two principal ones being the rateable value of the premises supplied in the case of 217 undertakings, and the size of premises (floor area or number of rooms, etc.) in the case of 161 undertakings.

A further analysis, supplementing the above, is now given to illustrate the general trend of tariff structure. This later analysis also provides an approximate indication of the manner in which the size-of-house and rateable-value tariffs are being adopted.

Table 1

Number of undertakings offering multi-part tariffs on the bases given below

	1931	1934	1937
Size-of-house	150	161	227
Rateable-value	125	217	231
Other bases	173	128	—
Total number of undertakings offering multi-part tariffs	448	506	—

The Report continues the analysis with a view to ascertaining the number of domestic premises supplied under two-part tariffs. Of the 506 undertakings supplying on two-part domestic tariffs in 1934, only 462 undertakings supplied the necessary particulars. For these 462 undertakings, however, 4 190 000 domestic premises were connected to the supply in 1934, and about 1 514 000 domestic premises were being supplied under two-part tariffs. About 706 000 of the 1 514 000 domestic premises, i.e. 16·8 per cent of the total of 4 190 000 under consideration, were offered a running charge of ½d. per unit, or less.

In 1938 a survey was published by the Electrical Development Association* which gave statistics relating to "the unit cost under the all-in tariffs offered by all the electricity supply authorities in Great Britain." These statistics are summarized in Table 2.

Table 2

Year	Number of consumers to whom a unit cost as given below was available		
	½d. per unit, or less	Between ½d. and 1d. per unit	1d. and over
1936	2 759 000	3 125 000	316 000
1938	4 682 000	2 783 000	223 000

Table 26 of the Engineering and Financial Statistics issued by the Electricity Commissioners provides the data given below in Table 3 which gives some indication of the general manner in which charges for electricity are being reduced.

It should be noted that the analyses given above, which are based upon the number of undertakings, without reference to the size of undertaking and the number of

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* Sixteenth Annual Report of The Electricity Commissioners.

* "The Truth about the Price of Electricity in the Home."

Table 3

AVERAGE REVENUE PER UNIT SOLD
ANALYSIS OF PARTICULARS FOR INDIVIDUAL UNDERTAKINGS

Average revenue obtained per unit sold	Number of undertakings		
	Year 1929–1930	Year 1933–1934	Year 1937–1938
	Lighting, heating, and cooking supplies		
Under 3d.	143	277	431
3d.–4d.	127	136	113
4d.–5d.	92	97	52 } 4d. and over
5d.–6d.	76	60	
6d.–7d.	62	31	
7d.–8d.	48	18	
8d.–9d.	32	15 } 8d. and over	
9d.–10d.	34		
10d. and over	20		
Total number of undertakings	634	634	596
	Power supplies		
Under 1d.	145	203	253
1d.–2d.	227	230	245
2d.–3d.	124	118	66
3d.–4d.	58	31	13 } 3d. and over
4d.–5d.	17	17 } 4d. and over	
5d.–6d.	11		
6d. and over	8		
Total number of undertakings	590	599	581

consumers connected, are not fully informative as to the real position. It is desirable that analyses of this nature should be based upon the number of consumers affected so as to show more fully the trend of charges and tariff structure. Unfortunately there are, at present, no sources from which this more accurate information may be obtained, and it is very desirable that accurate and fully informative statistics should become available.

(3) GENERAL TENDENCIES OF COSTS AND CHARGES

The Tendency of Charges for Supply

Fig. 1 shows the average price received per unit sold for the two main classes of supply during each year of the period 1921–1938. The prices are the average for all supply undertakings, based upon the data given in Table 23 of the Statistical Returns of the Electricity Commissioners. A continuous decrease will be noted in the charges for domestic supplies, and also an increased rate of consumption, as indicated by the increased horizontal distance between the points for each year, commencing from about 1932–33. For both classes of supply a small decrease in price has been accompanied by a much larger increase in consumption during the last three years than occurred in the earlier years of supply.

The curves show that the average price received by all undertakers for their whole supplies has fallen steadily for some years. This reduction reflects the many cuts in charges which have been made, but also the wider use of electricity at tariffs which, although the charges may not have been reduced, contain in themselves business-promotional features which are taken greater advantage of by the public each year as knowledge of electrical methods becomes more general. In short, a falling average return per unit is an index of the success of those "all in" tariffs upon which domestic and some other classes of electrification are now based.

The Tendency of Electricity Costs

Fig. 2 illustrates the manner in which the average cost of providing supply has fallen since 1921–22; the data for the curve of total cost are taken from Table 27 of the Statistical Returns of the Electricity Commissioners.* In general, the total cost of providing supply, per unit sold, has consistently been reduced in each year but to a decreasing extent during the 8 years which are covered

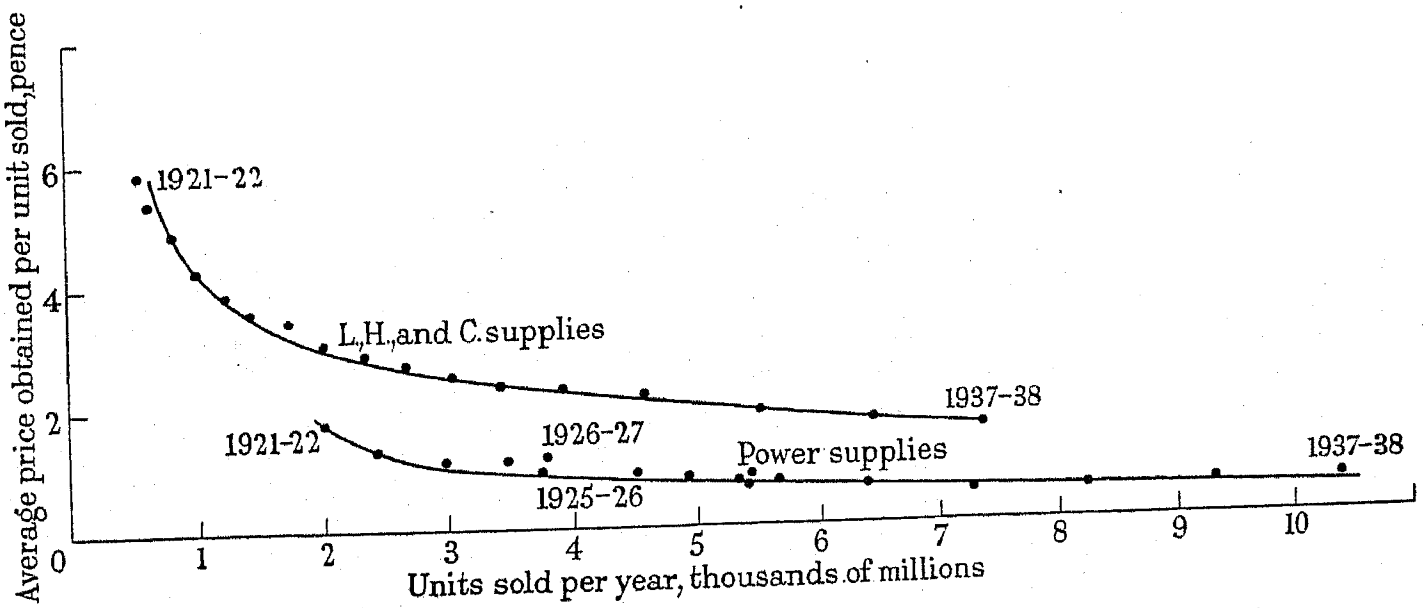

Fig. 1.—Average revenue received per kWh sold. Total for all undertakings in country.

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* See *Journal I.E.E.*, 1933, vol. 73, p. 101, and Table 6, for basis of calculation of component costs of distribution and generation.

by this review. Since the cost of providing supply must ultimately determine the charges which are made it is of some value to analyse briefly the present and possible future conditions of costs and charges.

Fig. 2 shows that the reduction in the cost of supply has been largely due to a reduction in the cost of generation, which is determined by three main factors—thermal efficiency of the generating plant, annual plant load factor, and cost of fuel and labour. Although the thermal efficiency of generation has improved in a remarkable manner over the last 20 years, it has been at a decreasing rate and it is probable that we are now approaching very closely to the maximum efficiency which can be obtained with the present methods of generation. As regards the annual plant load factor, the operations of the Central Electricity Board in reducing spare plant are taking place in a field which is continually diminishing as the C.E.B. scheme progresses. As regards the third factor—the cost of fuel—the supply industry has had to face a general and serious rise in the cost of coal, which has already proved to be so great as to offset more than the reduction in the cost of generation effected by other means. For 1936–37 the average increase in the cost of coal for the whole country was 1s. 8d. per ton. During 1937–38 the average cost of coal had risen to 18s. 6d. per ton, which represents an increase of 3s. 6d. per ton on the 1935–36 prices. On the C.E.B. scale of charges to supply undertakings, the 1937-38 coal cost of 18s. 6d. per ton represents an increase above the basic running price of the order of 0·078d. per kWh purchased from the C.E.B. and an increase of 0·042d. per kWh since 1936.

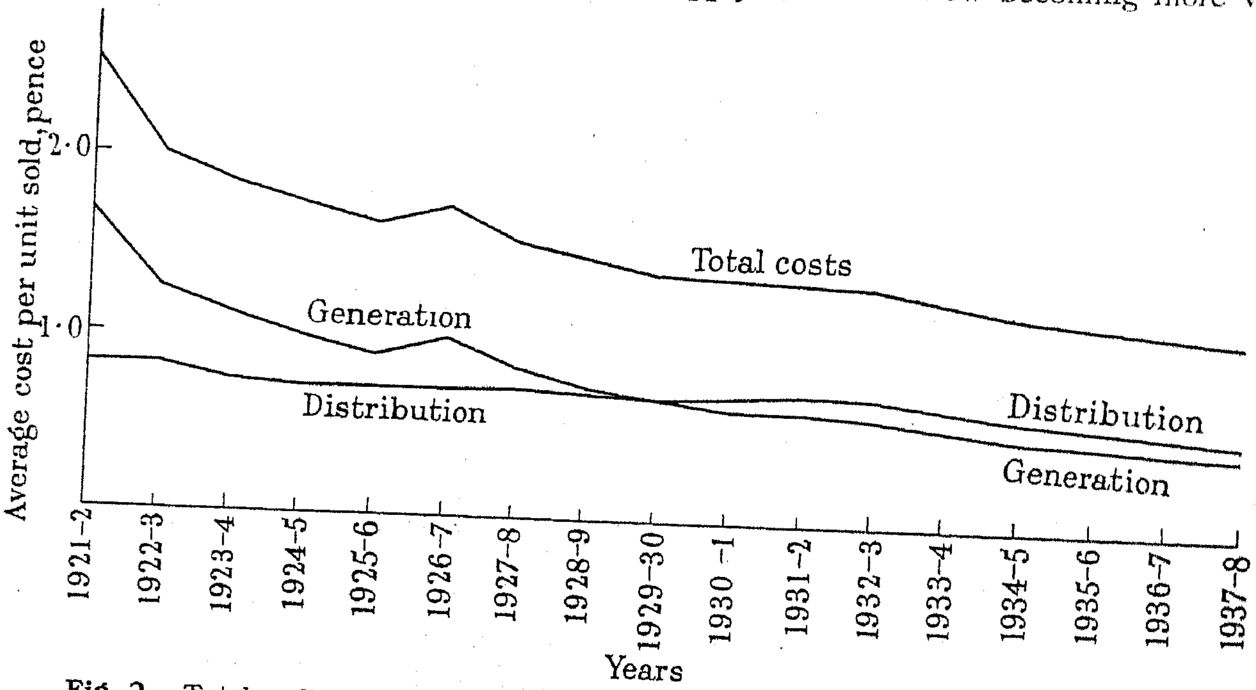

Fig. 2.—Total and component costs (per kWh sold) for all undertakings in country.

So far as generation is concerned, therefore, it will be seen that the three main factors which determine the cost are operating in a diminishing field, with the strong probability that the total cost of generation may actually increase when the full effects of the increasing coal costs are known, instead of being reduced as in previous years.

When we turn to the distribution side it will be seen that the potentialities for reducing costs are much greater. Here the factors of plant efficiency and load factor still operate to influence distribution costs, but in an increasing field of opportunity instead of a diminishing field as for generation. Although there has been an increase, during the last three years, in the costs of material and labour for distribution, added to increased costs of current from the C.E.B., the future for the cost of supply must lie with the distribution side of the industry, i.e. with supply undertakings who will require to increase sales and encourage the type of load which will improve the national load factor.

It is difficult to forecast the effect upon electricity tariffs and charges of the increase in the cost of coal, but it is certain that reductions in charges by supply undertakers may be deferred, and in certain cases an increase in charges has already taken place for domestic supplies as well as for industrial consumers who are taking supply on a bulk-supply tariff with a coal clause. The increase of charges by the C.E.B. to supply undertakings in respect of the increased price of coal is equivalent to a large proportion of the low secondary charges for domestic supply which are now becoming more widespread, e.g. ½d. and ⅓d. per kWh; the effect of the increase will almost certainly be to check in some measure the extension in the number of undertakings offering these low rates and slow down thereby the rate of increase in domestic consumption which has been stimulated during recent years by their wider offer.

Delay in reducing charges will therefore check an increase in consumption in those areas where prices have not yet fallen to a level which places electricity more or less on a cost parity with other forms of energy; but in many districts the form of tariff and actual rates charged are already so favourable to the consumer that the maintenance of the rate of progress achieved in recent years depends rather on advertising and the provision of wiring and apparatus on easy terms. Where tariffs of modern form are in use and the unit rate is low, say ½d. or less, delay in further reducing charges would not check the rate of increase in consumption as the average cost per unit of the supply to each consumer would continue to fall with his increasing use, whilst to the supply undertaking rising load factor and returns on capital invested, particularly in distribution, will advance the time when some further general reductions in tariffs would become possible, or would at least offset rising costs of construction and operation. It is not, however, to be expected that reductions in charges can be so frequent or extensive in the future as they have been in recent years.

Relationship between Price and Consumption

During the review period a considerable amount of attention and research has been devoted to ascertaining the manner in which price affects consumption. This examination of the economic aspect of electricity consumption has received so much attention during the last seven years as to justify comment in this review.

In 1931 Messrs. Dickinson and Grimmitt examined the consumption for 221 authorized undertakings providing rural supplies. These authors came to the conclusion that the units sold per consumer increase as the price falls and, more significantly, that the annual revenue from each consumer increases with the higher consumption, despite the reduction in price. For the 221 undertakings whose results (for 1929–30) were analysed the authors showed that the following formula applied:—

$$\begin{array}{l}\text{Average cost of providing}\\ \quad\text{supply to a consumer}\\ \quad\text{(in pence)}\end{array} = 1\,140 + 0{\cdot}73 \times \begin{array}{l}\text{(units}\\ \text{sold per consumer)}\end{array}$$

This expression provides an example of the reduction which can be achieved in the cost of providing supply if the consumer will improve his load factor. The fixed cost of 1 140d. and the running cost of 0·73d. per unit remain unaltered, but the average cost is reduced, e.g. if an original consumption of 1 140 units is increased to 2 280 units at the same load factor, the cost at which supply can be provided is reduced from 1·73d. per unit to 1·23d. per unit.

It is of interest that the curves published in the appendices to the McGowan Report (showing the average revenue per unit sold, annual consumption per consumer, and distribution costs per unit sold) provide formulae which support Messrs. Dickinson and Grimmitt's conclusions. For 1933–34 the McGowan Report curves provide the following formula showing the averages for all authorized undertakings:—

$$\begin{array}{l}\text{Average cost of providing}\\ \quad\text{supply to a consumer}\\ \quad\text{(in pence)}\end{array} = 1\,400 + 0{\cdot}5 \times \begin{array}{l}\text{(units}\\ \text{sold per consumer)}\end{array}$$

i.e. the fixed cost of 1 400d. is slightly more and the running cost less than for the 221 undertakings examined by Messrs. Dickinson and Grimmitt.

It is also of interest to note that the curves shown in Fig. 1 can be represented very closely by the following equations, during the years 1921–36.

$$\begin{array}{l}\text{Average charge per unit sold}\\ \quad\text{for lighting, heating, and}\\ \quad\text{cooking (in pence)}\end{array} = 1{\cdot}63 + \frac{2{\cdot}67 \times 10^9}{\text{units sold per year}}$$

$$\begin{array}{l}\text{Average charge per unit sold}\\ \quad\text{for power supplies (in pence)}\end{array} = 0{\cdot}26 + \frac{2{\cdot}6 \times 10^9}{\text{units sold per year}}$$

Those readers who are interested in the economic aspect of tariffs should refer to the following papers which have appeared in the *Journal*:—

E. W. Dickinson and H. W. Grimmitt: "A Distribution System in a Rural Area," 1931–32, vol. 70, p. 189.
J. M. Kennedy and Dorothy M. Noakes: "An Analysis of the Costs of Electricity Supply and Distribution in Great Britain," 1933, vol. 73, p. 97.
J. A. Sumner: "Modern Factors Affecting Electricity Costs and Charges," 1937, vol. 81, p. 429.
D. J. Bolton: "Electricity Demand and Price," 1938, vol. 182, p. 185.

(4) DEVELOPMENTS IN DOMESTIC TARIFFS

During the last few years a new factor has arisen to influence tariff development. An increasing proportion of consumers with a low annual income and living in small houses have been connected to the supply. These consumers are of the type who would not have been considered for supply purposes a few years ago, but the greater universality of electricity has made it practically impossible to-day for supply undertakings to ignore the consumers' right to have the convenience and service which an electricity supply affords, however small their consumption. It is generally acknowledged that the annual consumption of the small consumer is so low that the annual revenue which it provides is often inadequate to cover the cost of providing him with supply, even when high flat rates are charged; as a consequence modern developments are being directed towards devising methods of increasing the annual income from the small consumer. There has been a gradual appreciation by supply undertakers that these small consumers with a low income could not afford to purchase the same amount of apparatus for consuming electricity as the consumer with a higher income. Many supply undertakings have, for some years, provided the consumer's wiring installation and arranged for payments for this installation to be spread over a period of years. This development has been followed more recently by the supply undertakings providing cookers, and, later, other apparatus on a "hire" or "hire-purchase" basis. Some supply undertakings have considered that payment for the apparatus could be collected from the consumer quite satisfactorily by incorporating it in the charge made for electricity, and two tariffs introduced during the review period, designed to cover this payment, are:—

1) "Equated" Flat-Rate Tariff.

From a simple addition to the standard flat-rate charge per unit on either quarterly account or through prepayment meters, to cover repayment of apparatus, there was evolved the "equated" tariff* which has been used chiefly in the East London Boroughs. Under this tariff a charge is made, through an ordinary prepayment meter, on an equated flat rate based on the normal two-part tariff, i.e. the fixed annual charge under the two-part tariff is added to the annual prepayment charges for the apparatus provided, and this total sum is then divided by the estimated annual consumption so as to produce a price per unit which gives the "equated" flat-rate charge when the running cost is added. This type of tariff can only be applied to those consumers whose annual consumption can be previously estimated within fairly narrow limits.

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* See E.D.A. Publication No. 1310.

(2) "Finchley" Tariff.

A development of the "equated" tariff is one in which the supply undertaking provides consuming apparatus and makes no direct charge for it to the consumer, i.e. the consuming apparatus is considered as part of the distribution system necessary to provide a consumer with the benefits and service of electricity. In 1937 the Finchley supply undertaking obtained the approval of the Minister of Transport for the use of a tariff (under Section 42 of the 1926 Electricity Act) consisting of a periodical fixed charge, inclusive of the charge by way of hire in respect of certain apparatus and appliances and in addition a charge for the actual quantity of energy supplied. On the demand from any consumer on the two-part domestic tariff, the Finchley undertaking will provide an electric cooker together with its associated equipment; the apparatus is installed free of cost, without deposit, and without additional hire charge.

Collection of Fixed Charge by Prepayment Meter

During the period under review there has been a considerable development of meter technique so as to permit of the collection of the quarterly fixed charge under the two-part tariff by means of a prepayment meter. The early developments provided a single-element meter which revolved continuously at a speed proportionate to the given fixed charge and independently of the actual unit consumption, so that the supply was cut off after, say, the first week, even if no consumption of electricity was made; the use of current resulted in the meter disc increasing speed in the usual manner and thereby superimposing the revolutions of the disc due to normal load upon the biased no-load revolutions. This "biased" meter was then followed by other and more satisfactory types, e.g. the Fennell meter, and more recently by several types of meters which employ two distinct meter sections. In one section a synchronous motor is used to provide the continuous feature and is arranged to register the fixed weekly charge; the second section consists of the ordinary integrating kilowatt-hour meter.

"Load Rate" Method of Charging

An interesting variation introduced during the review period is the "load rate" method of charging by which a device is used which brings into operation alternative gears in the price gear train of the meter or may bring into use a second meter element, whenever a prescribed load is exceeded. The interesting feature of this method of charging is that the maximum demand of a consumer is fixed by the supply undertaking beforehand, and an "equated" charge per unit is made for consumption within this limit of maximum demand. The metering device makes it possible to charge a price per unit for consumption in excess of the prescribed maximum previously agreed, which may be arranged to be higher or lower than the "equated" price.

Tariffs for Special Hours of Use

Reference has been made earlier to the diminishing field which is available to the Central Electricity Board in reducing generation costs. It would seem that the initiative in reducing the total cost of providing supply must be taken now by the supply undertakings in the field of distribution, where the potentialities for improving the annual load factor are so much greater. There still remains the characteristic summer slump in the national load curve, which can only be filled by encouraging the use of apparatus such as refrigerators, fans, water heaters, etc. The encouragement of use of a variety of types of domestic consuming apparatus will also result in a higher diversity in the times of use.

As an alternative to the type of apparatus which is used chiefly during the summer, improvement in load factor may be obtained by offering specially low rates for apparatus which is in use only during the winter "off-peak" hours. During the last few years, however, there has been a sensible levelling of the daily winter load curve of many undertakings, which has resulted in a morning peak load approximating closely to that of the evening peak. During the review period, therefore, the tendency has grown to encourage supplies which will be used only from, say, 8.0 p.m. to 6.0 a.m. in the four winter months coinciding with the C.E.B. period of charge (see later note), and which may be used without any restriction during the 8 months remaining in the year. A recent technical development consists of superimposing a high-frequency impulse on the mains and operating thereby a relay on the consumer's premises which cuts load in or out, at the will of the supply undertaking. It may be possible by this means to control large blocks of load which can be operated so as to avoid the peak period of an undertaking and thus control load factor to a very much higher degree than has been possible in the past.

During the review period there has been a large increase in the number of undertakings who have offered specially low tariffs for domestic water-heating and refrigerator supplies. The technical difficulties which have been associated with switching off apparatus on a consumer's premises from a central control panel have led to a wider use at the substation of special rates for apparatus which requires a low electrical loading and will be likely to consume electricity over a large part of the day. Water-heating loads for domestic supplies, e.g. thermostatically-controlled water-heaters, with their large possibilities of heat storage, have therefore increased considerably and it should be mentioned that at least one supply undertaking has carried out development work in connection with a "storage-heat" cooker.

There has also been some progress in connection with the heating of large buildings by means of water heated electrically in large storage tanks. Storage of electricity in the form of heat energy offers wide possibilities for a supply undertaking to restrict loads to the "off-peak" periods. It is possible that the heating of large buildings by means of electrically heated water may make considerable strides in the near future if the price of raw fuel continues to increase, as this type of load may be restricted almost entirely to the night, when generating plant is lying idle.

(5) DEVELOPMENTS IN INDUSTRIAL TARIFFS

General

It does not appear that the developments in industrial tariffs have been so pronounced during the review period as the developments in domestic tariffs. This may be due to the relatively greater development of industrial power supplies and probably to the appreciation by supply undertakings of the wider field of development which is available in connection with domestic supplies.

Promulgation of C.E.B. Tariffs

A noteworthy feature of the review period is, however, the commencement by the Central Electricity Board of normal trading in all the districts in England, on the basis of a tariff fixed in accordance with the 1926 Electricity Act.

A two-part tariff has been adopted, varying but little between the Board's operating areas and generally consisting of a fixed charge per kilowatt per annum, measured during the four winter months, and graded from £3 10s. to £2 15s. per kW per annum in blocks, the size of which is related to the magnitude and circumstances of each undertaking, so to promote future development and have some regard for their enterprise in the past. The unit charges also vary a little in different areas, and adjustments are provided for power factors, rates, and fuel costs.

Those undertakers who buy in bulk from the Board at the tariff derive from the pooling of generating sources the advantage of being able to declare their estimated demand each year and so avoid the many commitments on overhead charges ahead of requirements which are incurred under independent generation whenever it becomes necessary to increase plant capacity.

The promulgation of the C.E.B. tariffs may exert a considerable influence upon tariffs in general and industrial tariffs in particular—upon tariffs because of the approach to a standard wholesale price for electricity, and upon industrial tariffs because of the decision of the C.E.B. to charge only for the maximum demand which is incurred during the four winter months.

Where electricity is purchased by industrial consumers in large quantities the most general form of tariff now used is a two-part tariff with a fixed charge per kW or kVA of maximum demand, and a running charge per kWh. The time period over which the fixed charge is considered is, however, widely variable between supply undertakings. In some cases the highest kW or kVA demand made during any one year is taken as the demand for purposes of charging, and in other cases the highest demand per quarter or per month is adopted. It will be noted that the F.B.I. Report on Tariffs does not make any recommendation on this matter.

In certain cases where the highest yearly demand is used as the basis of charge, the annual period of charge consists of the 12 months following and inclusive of the month in which the highest demand occurs, irrespective of the period of the year during which this high demand occurs, i.e. irrespective of whether it occurs in the 4 winter months during which the undertaking's demand on the C.E.B. is established or during the remaining 8 months of the year. This method of charging may often cause anomalies to arise, e.g. a consumer paying on a kVA basis may install power-factor-correction apparatus and thereby reduce his demand but will continue to pay for a further 11 months on the higher demand established immediately before the power-factor correction was installed. Or a consumer may establish a demand during one summer month which is higher than his normal demand during the remaining part of the year; where the supply undertaking is buying at the C.E.B. tariff this temporary summer demand will not increase the C.E.B. charge to the undertaking, despite which the consumer has to pay an increased charge over the whole year following his temporary increase in demand. There is an undoubted grievance felt by many industrial consumers who are penalized for a temporary "snap" demand, and it is to be hoped that supply undertakings who are now using a basis of "highest annual demand charges" will move towards standardization by calculating the consumer's fixed charge only on the maximum demand incurred by him during the 4 winter months corresponding to the period of charging adopted by the C.E.B. This method of calculation should be particularly capable of adoption by those undertakings which operate under Section 13 of the 1926 Act.

Restricted and Off-Peak Industrial Supplies

Reference has been made earlier to the contribution which the supply undertakings must make towards reducing the cost of supply by improving the national load factor. To a large extent this improvement must be met by encouraging summer-time loads such as refrigerators, and, to a lesser extent, water heating, both of which are in the domestic field. There has, however, been a new field opened to industrial supplies in the development of the electric furnace load. Electric furnaces have proved particularly successful in the last few years for such purposes as the annealing and heat treatment of metals, and, in general, this class of load is a long-hour load with a high load factor. But the use of electric arc and induction furnaces for melting iron and steel has recently achieved considerable success and should prove to be a type of load with a high load factor, provided suitable "off-peak" rates are offered. A very flexible control of demand is available for electric furnace loads of this type, permitting low rates to be offered in return for a restriction of load at certain times. Further, the recent increases in the price of coal and oil fuel may weight the scales still further in favour of electricity, and the time would seem to be ripe for an authoritative investigation into the cost of reducing steel or iron by means of electricity. There appears to be a general understanding that the "all-in" cost of electricity must not exceed 0·3d. per kWh if it is to compete with coal for steel and iron production, but is it not possible that the cost of electricity should be related to the selling price of steel, in the same manner that cable costs are related to the basic price of copper?

SUMMARY OF PROGRESS

During the 8 years which are covered by this review there has been a remarkable increase in the consumption for domestic and power supplies. The total consumption in Great Britain for domestic use only is now nearly equal to the combined consumption for both domestic and power supplies in 1930–31, and the rate of increase for both classes of supply has been steadily improving during each year in the review period.

This increase in consumption has been accompanied by a consistent reduction in the average charges (see

Fig. 1) due to actual reduction in charges in the case of many undertakings and also to an increase in the consumption on multi-part tariffs which has resulted in the consumer obtaining a lower average price as his consumption increases at the lower secondary rates.

It is not possible to state the extent to which the reduced charges account *directly* for the increase in consumption, as it has to be noted that since 1930 there has been an increase in the number of consumers which is no less remarkable than the increase in consumption. The total number of electricity consumers in Great Britain has increased from 4·01 millions in 1930–31 to 8·56 millions in 1936–37, an increase of 110 %, and it is estimated that 85 % of these consumers are taking supply for lighting, heating, and cooking, i.e. for domestic purposes. (It should be noted that this classification includes shop and office lighting and heating.)

In general, the review period has been characterized by falling charges, particularly for domestic supplies, and probably by a large increase in the number of domestic consumers who now take their supply on a multi-part tariff for all purposes instead of at flat rates. The average charge for power supplies has fallen much less than the average charge for domestic supplies, as was to be expected in view of the much lower average at which power supplies are obtained; despite this, the annual rate of increase in the total power consumption has grown rapidly during the last three years.

The recent increases in the price of coal may effect a radical change in the structure of electricity charges, which is founded upon a system of low prices for power supplies and high prices for domestic supplies. Because domestic supplies are highly elastic and as a consequence are very sensitive to any alteration in the average price level, there is likely to be a sharp check on domestic consumption if domestic supply prices increase; on the other hand, the more inelastic power supplies are not so likely to be checked as a result of electricity prices being advanced. It is therefore quite possible that the increased charges which the rise in coal prices make necessary will be passed on largely to power consumers (most of whom have a coal clause in their supply agreement), and thereby tend to reduce the present disparity in the charges for the two classes of supply.

In general, there has been during the review period a rapid growth in the consumption of electricity and the connection of consumers, at a rate probably unparalleled in the history of electricity supply. But this expansion has caused a very large increase in distribution capital expenditure, much of which is not yet fully remunerative, and particularly that portion which has been expended to supply a new class of small and low-income consumers. The consumption for 1938 indicates a slight recession in the previous rates of increase in consumption, and this makes it even more imperative, therefore, that the work of the immediate future should consist of a process of consolidation of the present favourable position of consumption. Increasing costs of supply must be countered by retaining, or even lowering, the present charges for domestic supply, and by so extending the two-part tariff that increasing consumption will develop the loads on mains and effect an improvement in the diversity and load factor and so result in a greater return on the invested capital and also in an actual reduction in the costs of distribution.

THE ELECTRICAL PROTECTION OF COLD-CATHODE LUMINOUS DISCHARGE-TUBE INSTALLATIONS

By H. M. BARLOW, Ph.D., Associate Member.[*]

(*Paper first received* 12*th September, and in revised form* 24*th October*, 1938; *read before the* METER AND INSTRUMENT SECTION 3*rd February*, 1939.)

SUMMARY

The importance of providing adequate protection against the risk of fire and electric shock due to faults developing on high-voltage discharge-tube circuits has recently come into prominence on account of the extensive use of such apparatus for industrial purposes. The paper explains the peculiar difficulties met with in devising suitable protective devices, and, after describing the principal types of equipment at present available, gives details of certain recent developments for which the author has been responsible.

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(1) Introduction.
(2) Sources of Danger, and Protection Desired.
(3) Protective Devices at present Available.
(4) Recent Developments in Protective Devices.
    (*a*) Relay system controlled by distribution of magnetic flux in core of supply transformer.
    (*b*) Relay system controlled by interruption of current through discharge tube.
(5) Acknowledgments.

(1) INTRODUCTION

The problem of providing a satisfactory system of electrical protection for neon signs and other cold-cathode gaseous discharge-tube installations is beset by difficulties inherent in the apparatus employed. Under ordinary operating conditions the discharge tube has a negative resistance characteristic such as Curve (*a*), Fig. 1. In order to obtain stability with the usual a.c. supply, some form of inductive reactance is almost invariably included in the circuit so as to give at the terminals of the discharge tube a voltage which falls rapidly with a small increase of current, as shown in Curve (*b*), Fig. 1. Such reactance may be provided by increasing artificially the leakage flux of the supply transformer, or, alternatively, by choking coils in series with either the primary or the secondary circuit of the transformer (Fig. 2). The result of these arrangements is to produce an approximately constant current through the discharge tube at a voltage which adjusts itself automatically to the length of tube employed.

In the majority of cases a transformer having a comparatively large leakage reactance is used to feed the discharge tube, and even when the secondary terminals are short-circuited the secondary current seldom exceeds its normal value by more than 20 per cent (see Fig. 1). The variation of primary current is also relatively small whatever the conditions of operation on the secondary side. It is apparent, therefore, that satisfactory protection against a leakage fault on the secondary circuit cannot be provided by the use of a current-operated fuse or circuit-breaker in series with either winding of the transformer. A fault on the primary circuit is, of course, quite a different matter and requires no special consideration.

Another feature of cold-cathode gaseous discharge tubes which is of importance in connection with measures for electrical protection is the high striking voltage compared with the normal running voltage [see Curve (*a*), Fig. 1], and the sudden extinction of the discharge when the voltage falls to a value insufficient to maintain ionization. Thus the open-circuit secondary voltage of the transformer is generally some 35 per cent greater than the maximum permissible running voltage. A high-resistance parallel circuit of 100 000 ohms or more across the secondary will generally cause the discharge

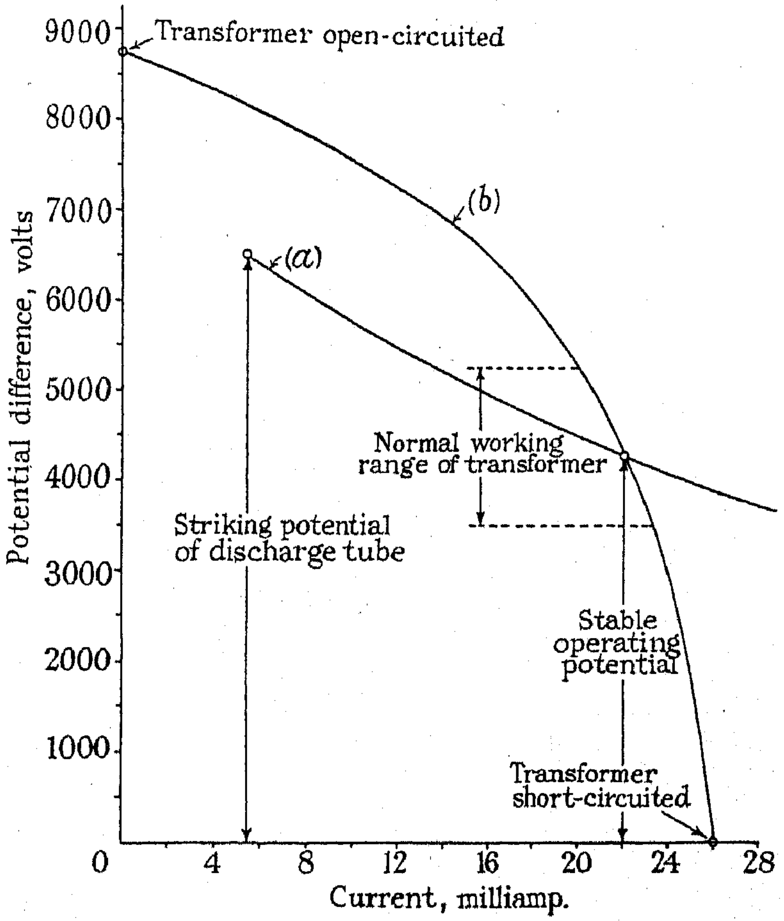

Fig. 1.—Typical discharge-tube characteristic and voltage-regulation curve for transformer.
(*a*) Discharge-tube characteristic.
(*b*) Transformer characteristic.

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[*] University College, London.

tube to go out, with the result that the total current taken from the secondary may, in some cases, be actually less with than it was without the parallel circuit.

(2) SOURCES OF DANGER, AND PROTECTION DESIRED

The recent rapid extension of the use of cold-cathode gaseous discharge tubes for lighting, advertising, and display purposes, has made it imperative that adequate protection should be provided against the risk of fire and electric shock when a fault develops on the tube circuit. Supply voltages from 2 000 to 15 000 volts are necessary to operate these tubes economically, and they may become a source of danger in the following ways: A tube or connection may break, causing interruption of the high-voltage circuit. Such a breakage is usually accompanied by the formation of an arc, which, if maintained for any considerable time, may set alight the rubber-covered wiring or any other inflammable material in the immediate vicinity. Should the breakage cause a complete interruption of the tube circuit there is nothing to indicate whether the high-voltage supply has been cut off or not, and if the apparatus be inadvertently handled when the equipment is alive there may be serious results. Again, a bad earth fault may occur on the tube circuit without any appreciable change of current in the primary circuit of the supply transformer. Thus a leak may remain undetected over a long period of time, causing charring of woodwork in the neighbourhood of the apparatus and an outbreak of fire.

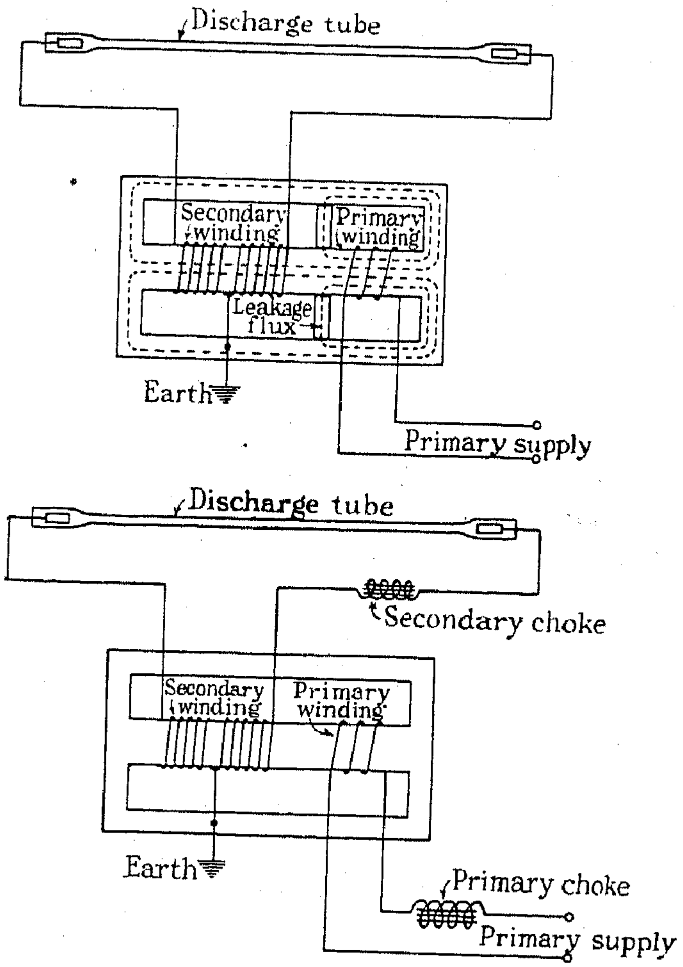

Fig. 2.—Circuit arrangements for feeding discharge tubes.
Upper circuit.—Control of current by transformer leakage reactance.
Lower circuit.—Control of current by choking coils.

The London County Council Fire Brigade report that the number of fires in London directly attributable to faults developing on luminous discharge-tube installations was 45 during 1936 and 61 during 1937.* The number of such fires is apparently increasing, and this in spite of full protective measures on the primary side of the supply to the discharge-tube transformers.

What is therefore required is a device operating automatically to interrupt the primary supply, so that the whole installation becomes dead, as soon as an open-circuit or an earth-fault appears on any part of the high-voltage wiring to the discharge tubes. Since metal parts used in the construction of the apparatus and one point on the secondary winding of the transformer are always earthed,† a short-circuit independent of earth is practically impossible.

The effects of electric shock on the human body vary widely, but it is generally agreed that current is the principal factor determining the intensity and nature of the shock. The threshold of decontrol, i.e. the current value at which a person ceases to have control over his muscles, is found‡ to be about 15 milliamp. at a frequency of 50 cycles per sec., and in order to afford a proper measure of protection against electric shock it is therefore necessary to ensure that the supply is cut off as quickly as possible when the leakage current approaches that value. Numerous tests on animals of several species comparable in size with man show that the threshold of ventricular fibrillation, which is usually fatal, is about 100 milliamp.

Finally, it is important that any protective device employed should not interfere with switching operations on the primary circuit of the supply transformer, whether these be for ordinary control or for flashing the discharge tube.

(3) PROTECTIVE DEVICES AT PRESENT AVAILABLE

The commonest form of protective device at present available is designed to interrupt, by means of a fuse, the primary circuit of the transformer supplying the discharge tube when an open-circuit occurs on the secondary.§ For this purpose the increased secondary voltage accompanying the removal of the load is employed to cause the breakdown of a spark-gap across the secondary terminals, and in so doing to melt the fuse wire which is situated in the path of the discharge (Fig. 3). In some cases the fuse wire actually carries the primary current which is thereby interrupted, and in others the breaking of the fuse wire releases a spring tending to open a switch in the primary circuit. These devices only aim at giving protection against open-circuit faults on the discharge-tube circuit, and, unfortunately, even in this restricted field of application they cannot be regarded as reliable. They depend for their action on the breakdown of a spark-gap when the voltage across it rises by about 25 per cent or less, from the striking potential of the discharge tube to the peak value of the transformer potential on open-circuit, and it is well known that the accurate adjustment of such a gap for the varying conditions of temperature, humidity, and cleanliness met with in practice, is almost impossible.

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* These figures were kindly supplied by the Chief Officer of the London Fire Brigade.

† British Standard Specification No. 559—1938.

‡ L. P. Ferris, B. G. King, P. W. Spence, and H. B. Williams: *Electrical Engineering*, 1936, vol. 55, p. 498; and M. H. Ourson: *Revue Générale de l'Électricité*, 1934, vol. 35 p. 779.

§ Extract from British Patent Specifications Nos. 334896 and 450785 and 472312, by permission of the Controller of H.M. Stationery Office.

Another device employed* is arranged to short-circuit out any section of a discharge-tube system which, by reason of a fault, would otherwise cause an interruption of the circuit. The remaining sections will thus continue to operate. This is achieved (Fig. 4) by an electrostatically operated by-pass element consisting of a highly evacuated glass tube containing two flexible spring electrodes having a small gap between them and connected one to each end of a particular section of the gaseous discharge tube. Should this section of the discharge tube cease to conduct electricity, the voltage across it will rise sufficiently to draw together the two flexible electrodes in the by-pass element, and the flow of current when the contact is made causes the electrodes to be welded together and to remain thus. When the fault has been cleared the by-pass element can be restored to its normal open-circuit condition by tapping the glass tube. This device, which is intended to localize the effects of a fault, will not prevent the transformer from continuing to feed current to earth through defective insulation. Moreover, there are obvious difficulties in connection with vibration of the flexible electrodes contained in the by-pass element, particularly due to resonance effects arising from mechanical or electrical forces. There is also the undesirable effect of the by-pass elements and the wiring thereto in increasing the capacitance in the discharge-tube circuit.

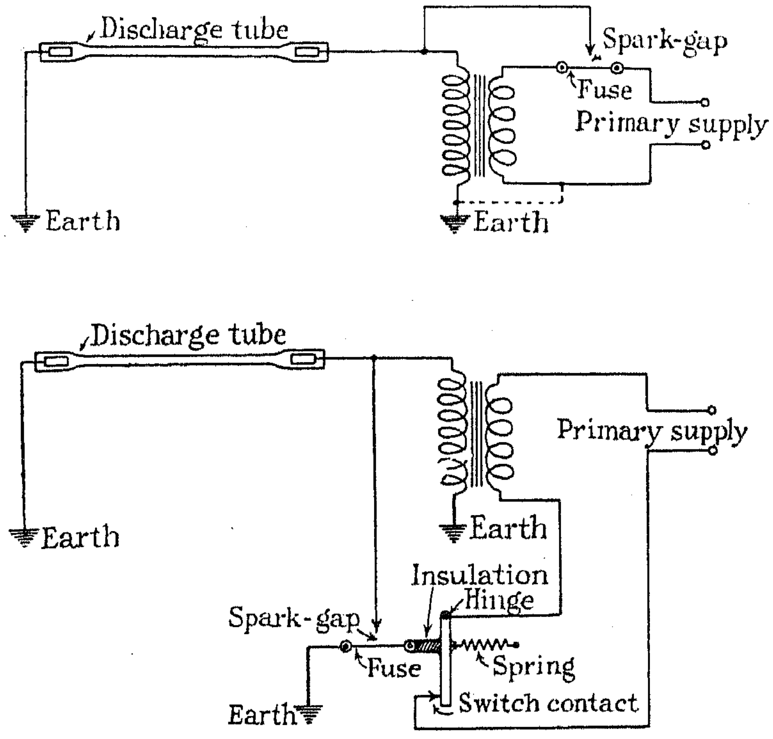

Fig. 3.—Protection against open-circuit faults.

For earth-fault protection a simple system† utilizes an electromagnetic relay which operates to interrupt the primary circuit of the transformer supplying the discharge tube when current flows through the connection to earth from the secondary circuit (Fig. 5). The relay coil is in series with this earth connection, and when energized operates on an armature to open a mercury switch controlling the primary supply. For comparatively large earth-fault currents this arrangement is quite effective, but leakage currents of 15 milliamp. or less, if allowed to continue unchecked through wood or other inflammable material, may easily start a fire, and a relay of this type cannot be expected to be completely reliable under such conditions. Moreover, the apparatus makes no provision for protection against the danger of an open-circuit fault.

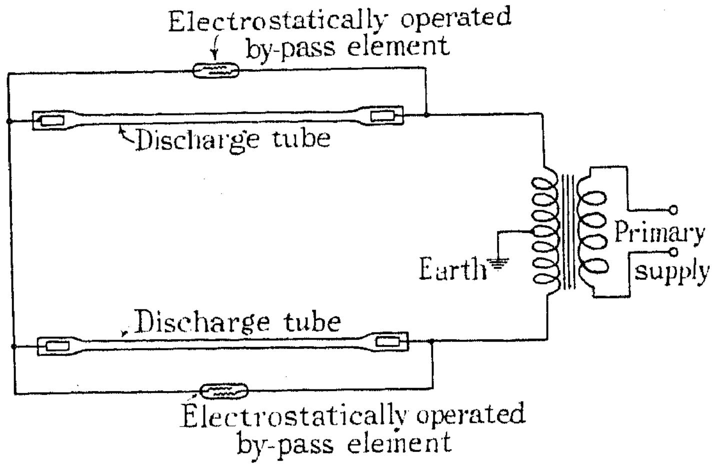
Electrostatically operated by-pass element
Discharge tube
Primary supply
Earth
Discharge tube
Electrostatically operated by-pass element

Fig. 4.—Protection against open-circuit faults.

(4) RECENT DEVELOPMENTS IN PROTECTIVE DEVICES

Some recent developments* for which the author has been responsible are an attempt to give a more complete measure of protection and greater reliability than was possible with apparatus previously available. An effort has been made to provide a single unit readily applicable to any of the usual types of discharge-tube installation and possessing the sensitivity necessary to operate with certainty on both open-circuit and earth faults likely to be a source of danger.

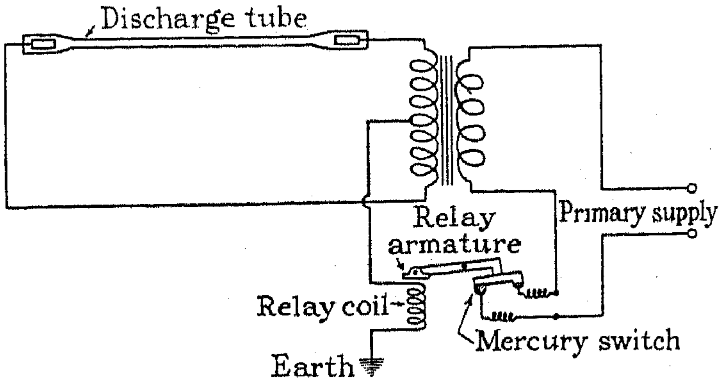

Fig. 5.—Protection against earth faults.

Two systems, both employing electromagnetic relays but depending for their action on different principles, have been devised.

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* Extract from British Patent Specification No. 460172, by permission of the Controller of H.M. Stationery Office.

† Extract from British Patent Specification No. 415236, by permission of the Controller of H.M. Stationery Office.

* Patents applied for.

(a) Relay System Controlled by Distribution of Magnetic Flux in Core of Supply Transformer

(i) Principle of operation.

This system (Fig. 6) makes use of the comparatively large leakage flux which is characteristic of transformers supplying discharge tubes. Thus a short-circuit or earth fault on the discharge-tube circuit causes only a minor alteration in the value of the flux linking the primary winding, whilst the flux linking the secondary winding falls to a relatively small value by reason of the increased flux leakage. Conversely, an open-circuit to the discharge tube is accompanied by a rise in the flux linking the secondary winding and a corresponding reduction in the leakage flux.

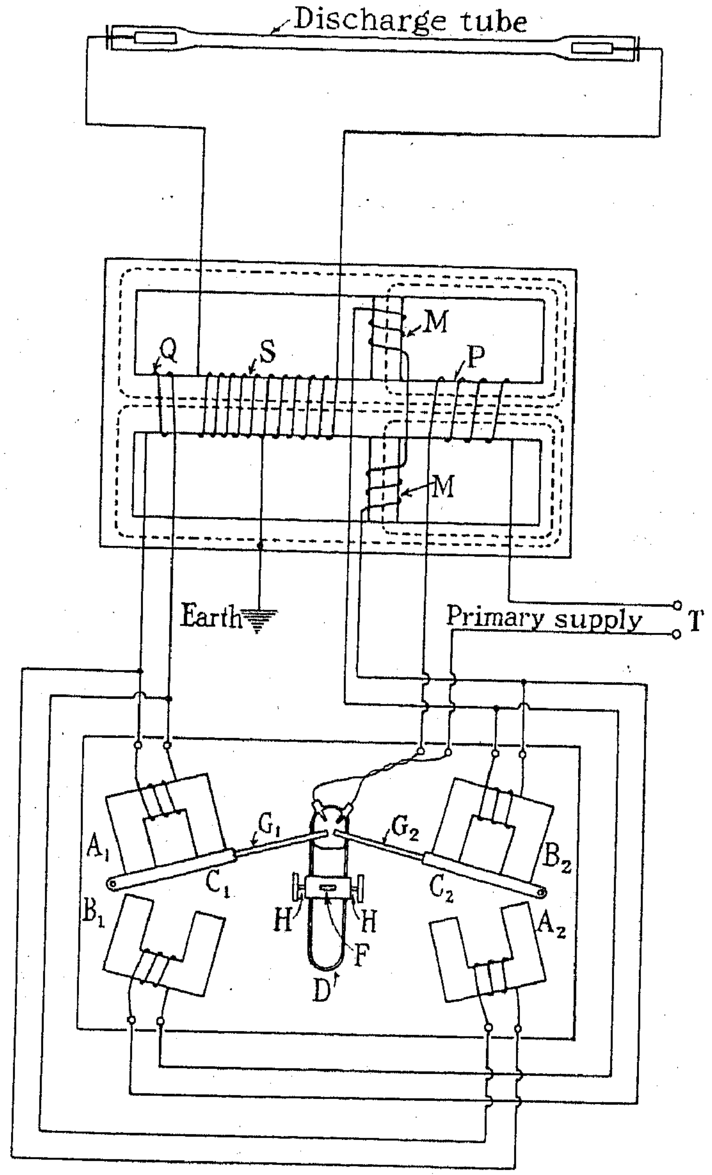

Fig. 6.—Protection against overload and open-circuit faults (system controlled by flux distribution in transformer core).

Two additional windings, Q and M, each of about 20 or 30 turns, are placed on the core of the transformer so that the e.m.f. induced in one winding is produced by substantially the same flux as links the ordinary secondary coil, and that in the other winding is produced by the leakage flux. These additional windings supply current respectively to the coils A and B of each of the two differential electromagnetic relays. The armatures C_1 and C_2 are quite independent and free to move into contact with the poles of either one or the other of their associated electromagnets. Under ordinary operating conditions the armature C_1 is held in contact with the poles of the electromagnet A_1 and the armature C_2 in contact with the poles of the electromagnet B_2, the armatures remaining thus when the a.c. supply to the terminals T is disconnected.

If an overload occurs on the secondary of the transformer the currents in the windings of the electromagnets A_1 and A_2 fall rapidly, whereas the currents in the windings of the electromagnets B_1 and B_2 rise. The armature C_1 is therefore pulled over into contact with the poles of B_1, and in so doing opens the small mercury switch D by rocking it about the spindle H, when the arm G_1 strikes the projection F. At the same time the armature C_2 is held with an increased force against the poles of the electromagnet B_2, and therefore remains at rest. If an open-circuit occurs on the secondary of the transformer, the currents in the windings of the electromagnets B_1 and B_2 fall to a small value, whereas the currents in the windings of the electromagnets A_1 and A_2 rise, causing the armature C_2 to be pulled over into contact with the poles of A_2 and again opening the mercury switch D. Thus the transformer supply is automatically interrupted under both overload and open-circuit conditions.

The effect of an earth fault on the secondary of the transformer is the same as the effect of a short-circuit, since one point on the secondary winding must be connected to earth and it is immaterial, for the purposes of this device, whether the fault involves one half or the whole of the winding. The armatures C_1 and C_2 remain in the " off " positions until pushed back again into the ordinary working positions.

Owing to the difference of phase and wave-form between the currents derived from the additional transformer windings Q and M, it is not possible to obtain the required opposition effects by connecting these coils in series. Instead of the coil M wound over the leakage-flux circuit of the transformer, it is generally more convenient to employ two coils connected in opposition and placed on the core, one beside the ordinary primary winding and the other beside the secondary.

(ii) Limitations of the system.

This system, although providing reliable protection against the majority of faults occurring in practice, is not so sensitive as might be desired in responding to small currents flowing to earth. Mention has already been made of the effect of a high-resistance parallel circuit across the discharge tube in causing the potential to fall below the value required to maintain ionization, and thus relieving the secondary of the transformer of the discharge-tube current. If then the secondary voltage does not rise sufficiently to restrike the tube, the load on the transformer may actually be less than when working normally. Under fault conditions of this kind the relay will not, of course, operate.

Another disadvantage of the system, from the practical point of view, is that the transformer must be provided with the special additional windings Q and M, although these can usually be readily accommodated on any standard core.

(b) Relay System Controlled by Interruption of Current through Discharge Tube

(i) Principle of operation.

The operation of this system (Fig. 7) depends upon the effect of a fault on the discharge-tube circuit in causing an interruption of the current through that circuit. Thus any appreciable leakage to earth reduces the voltage applied to the tube below that required to maintain the discharge, and the current through the tube falls to zero. An open-circuit naturally leads to the same result.

If the middle point of the secondary winding of the supply transformer is earthed, two differential electromagnetic relays are employed—one operating to interrupt the primary supply when a fault occurs on one side of the earthed point of the secondary circuit, and the second operating when similar conditions prevail on the other side of the earthed point.

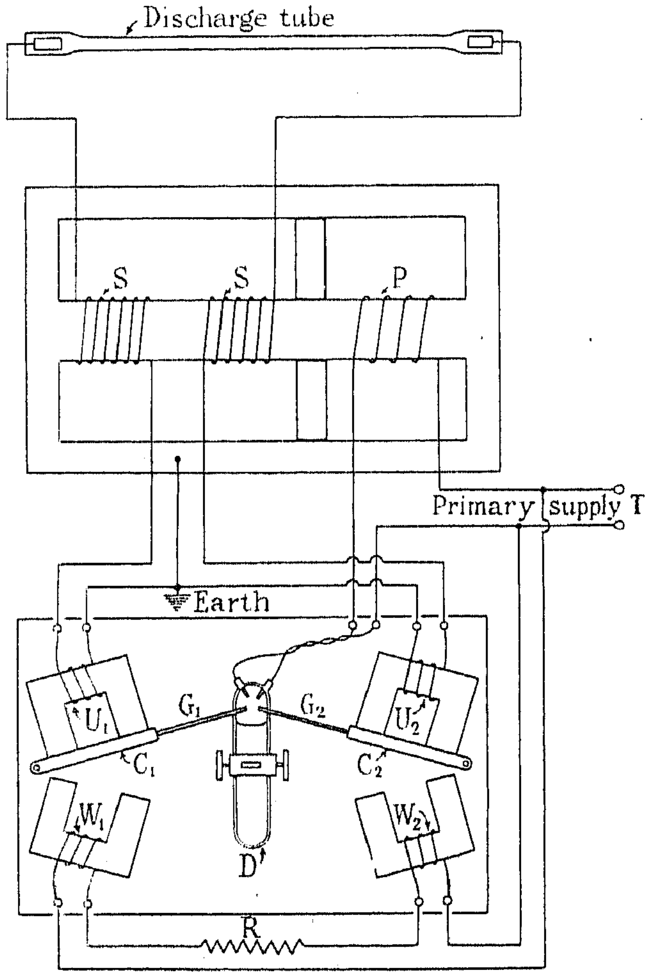

Fig. 7.—Protection against open-circuit and earth faults (system controlled by interruption of discharge-tube current).

The electromagnets U and W are supplied with currents derived respectively from the secondary winding and from direct connection to the primary supply. Under ordinary operating conditions the armature C_1 is held in contact with the poles of the electromagnet U_1, and the armature C_2 in contact with the poles of the electromagnet U_2, the armatures remaining thus when the a.c. supply to the terminals T is disconnected.

If an earth fault occurs on the left-hand side of the earthed point of the discharge-tube circuit, the left-hand half of the secondary winding becomes more heavily loaded, causing a reduction of the terminal voltage of the secondary winding as a whole; and, if the change is sufficient, ionization in the discharge tube will cease, bringing the current through it to zero. In such circumstances the right-hand half of the secondary winding, and with it the winding on the electromagnet U_2, will carry no current. The electromagnet W_2 remains energized, so that the armature C_2 is pulled over into contact with the poles of W_2 and in so doing opens the rocking-type mercury switch D. At the same time the left-hand half of the secondary winding and with it the winding of the electromagnet U_1 carries the earth-leakage current, and this will usually be sufficient to retain the armature C_1 in contact with the poles of the electromagnet U_1, but it is immaterial whether or not this armature is released simultaneously.

If an earth fault occurs on the right-hand side of the earthed point of the discharge-tube circuit the process is similar, with an interchange of the operation of the relays.

In the case of an open-circuit, the accompanying interruption of the current through the windings of electromagnets U_1 and U_2 causes the armatures C_1 and C_2 to be pulled over into contact with the poles of W_1 and W_2 respectively, both operating to open the mercury switch D. The armatures remain in the " off " positions until replaced in the ordinary working positions.

In cases where the secondary winding is earthed at one end, a single differential relay with the accompanying switch is sufficient to give full protection.

A single differential relay may also be employed when the earth-potential point of the circuit through the discharge tubes is accessible, so that the winding U of the relay can be connected in series at that point.

These arrangements apply whether the current through the discharge tube is derived from a transformer or from any other source having the necessary high percentage voltage regulation, whether alternating or direct current, interrupted, or otherwise.

(ii) Function of resistance in series with operating coils.

The resistance R serves to adjust the normal current through the operating coils W_1 and W_2 to a suitable value, and also has the important function of limiting the initial rush of current through this circuit which would otherwise occur sometimes when the supply was switched on. If it so happens that the supply circuit is closed at the instant when the voltage is zero, the transient current through these highly inductive relay coils, accompanied by the delayed striking of the discharge tube, may cause the armature to pull over and open the mercury switch. By making the resistance of the circuit through W_1 and W_2 high compared with its reactance, any transient effect of this kind is made negligible. Another method of achieving the same result is to include a condenser in series with W_1 and W_2 so as to produce resonance in the circuit and a gradual rise of current when the supply is switched on.

(iii) Use of magnetically operated mercury switch.

Instead of the rocking type of mercury switch in the primary circuit of the transformer, a magnetic type

(Fig. 8) is more convenient in most cases. In the normal position the rod-shaped armature of each differential relay itself bridges two mercury contacts contained in a small vacuum tube. So long as the supply to the terminals T remains on, the electromagnets W_1 and W_2 remain energized, so that when the armatures C_1 and C_2 are lifted vertically to break the contacts of the mercury switches D_1 and D_2 they are held against the poles of W_1 and W_2. Interrupting the main supply to the terminals T immediately resets the armatures in their normal working positions, and if a fault on the circuit has not been cleared before the supply is again connected to the terminals T the trip system operates automatically with such rapidity that no damage can be done. This arrangement has the obvious advantage of remote control for the purpose of resetting the relays, which would naturally be placed near the transformer or other supply service with which the protective device is associated, sometimes in very inaccessible positions.

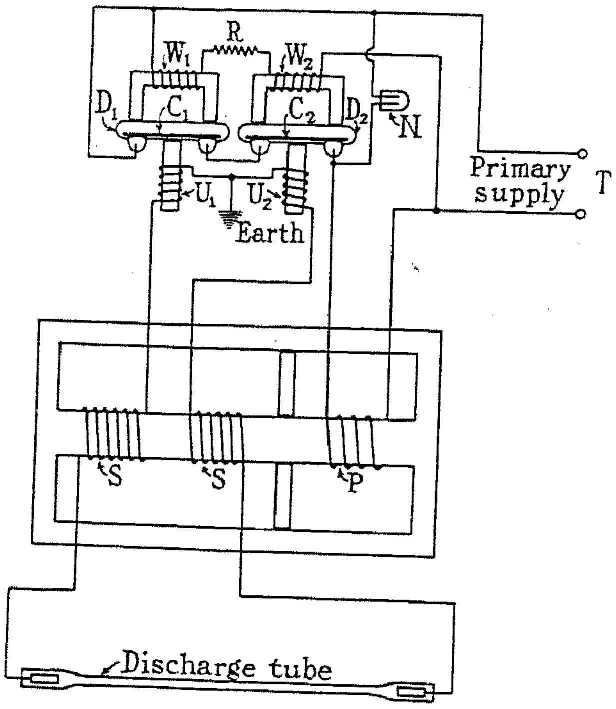

Fig. 8.—Protection against open-circuit and earth faults (system controlled by interruption of discharge tube current).

(iv) Indicator lamp.

A small neon indicator lamp N (Fig. 8) connected in parallel with the mercury switch may be used to show when the relay has been operated. The current through this indicator with the mercury switch open is too small to energize the transformer. The indicator lamp is particularly useful when a number of transformers are employed, as in the case of a large installation.

(v) Effect of capacitance.

The operation of this protective system is not affected by the connection of a power-factor-correcting condenser across the primary supply.

The capacitance to earth of the high-voltage leads to the discharge tube is also of little importance in this respect. The current flowing to earth through the capacitance of these wires is never large enough to interfere appreciably with the working of the relay, but the influence of this capacitance in improving the voltage regulation of the transformer may make the apparatus a little less sensitive.

(vi) Arrangement of transformer and housing of protective device.

No alteration is necessary in the arrangement of the supply transformer except that the ends of the secondary winding which are usually earthed to the core must be brought out to insulated terminals. The protective device can then be housed either in the transformer case, or, what would no doubt be more convenient with an existing installation, in a separate box hung on the side of the transformer case.

(vii) Provision for installations of different current ratings.

To provide for discharge tubes of different current-carrying capacity the relay coils U_1 and U_2 require to be made in two sizes, one suitable for any current from 15 to 35 milliamp. and the other for currents from 30 to 65 milliamp. The average ampere-turns are the same in the two cases, so that the dimensions of the coils remain unchanged and the design of the apparatus is not affected.

(viii) Power dissipated by protective device.

Whatever the value of the current carried by the discharge tube, no alteration is necessary in the circuit of the operating coils W_1 and W_2, and the power dissipated by this circuit is always 0·5 watt. The circuit of the retaining coils U_1 and U_2 has a power consumption which may vary from a small fraction of a watt up to 1·5 watts. The total power consumption of the complete protective device does not therefore exceed 2 watts.

(ix) Construction and size of protective device.

The construction of this protective device is particularly simple, consisting of four U-shaped electromagnets, the poles of which support the two mercury switches. The iron cores of the electromagnets are made of soft iron, the dimensions being so small that no lamination is necessary. The complete unit, including the neon indicator lamp, is mounted in a box measuring $3\frac{1}{2}$ in. × $2\frac{3}{8}$ in. × 2 in. and filled with wax to prevent the possibility of corrosion of any of the parts. The leads are brought out at the back through a hard-rubber multiple cable.

(x) Sensitivity of the device to faults.

The sensitivity of the apparatus in giving protection against faults depends to some extent upon the voltage regulation of the supply transformer, its percentage loading, and the nature of the gas employed in the discharge tube.

In the great majority of cases a current of from 10 to 15 milliamp. to earth is easily sufficient to arrest the ionization in the discharge tube and thus to operate the relay system. If the tube loading on the transformer is particularly heavy, a much smaller leakage current than this may bring the protective apparatus into action. The open-circuit trip will usually prevent an arc more than about $\frac{1}{8}$ in. long from being drawn out at the point where the interruption occurs.

In general, any fault, whatever its nature, sufficient to reduce the current through the retaining coils U_1 and U_2 of the relay to 6 milliamp. in the case of the smaller-current (15 to 35 milliamp.) apparatus and to 12 milliamp. in the case of the larger-current (30 to 65 milliamp.) apparatus, can always be relied upon to interrupt the supply to the transformer.

(xi) Special advantages of the device.

Apart from the advantages of remote control, simplicity of construction, rapidity of action, and the ease with which the device can be fitted to any discharge-tube installation, the following features are of special importance. There are no moving parts operating in air, and no electrical contacts to get out of order. No springs or hinges of any kind are used, and no delicate adjustments are required. Although the armatures are gravity-controlled the apparatus will work with equal reliability when tilted to any angle up to 40° from the horizontal in any direction. The relay is practically silent and can therefore be used for interior discharge-tube lighting installations. There is no tendency for an armature to stick, since it is always separated from the poles of its associated electromagnet by the glass wall of the mercury switch. The power dissipated by the apparatus, namely 2 watts (maximum), is quite negligible compared with the service it is capable of rendering. The complete unit, being surrounded by wax in a metal box, is practically proof against interference on the part of incompetent persons. When a protective device of this kind is employed special fire-resisting materials for the background and mounting of discharge tubes become unnecessary.

The apparatus has recently been put into commercial use, and in due course will no doubt be called upon to demonstrate its practical value. A working model has also been installed at the Home Office Industrial Museum, Horseferry Road, London, where it can be tested by anybody interested.

(5) ACKNOWLEDGMENTS

In conclusion, the author desires to acknowledge his indebtedness to his father, Mr. L. Barlow, Member, and to Mr. H. C. Vereker, B.Sc., Associate Member, for invaluable assistance in the practical development of the differential relay apparatus described; also to Prof. R. O. Kapp, B.Sc., Member, for placing at his disposal the facilities of the electrical engineering laboratories at University College, London.

[The discussion on this paper will be found on page 309.]

AN ELECTROSTATIC ANALYSER FOR COMPLEX WAVES OF SMALL AMPLITUDE

By Professor J. C. PRESCOTT, D.Eng., Associate Member[*]

(*Paper first received* 10*th May, and in revised form* 11*th July*, 1938; *read before the* Meter and Instrument Section 3*rd February*, 1939.)

SUMMARY

The paper describes a method of harmonic analysis in which the selective properties of the quadrant electrometer are utilized. The major portion of the energy necessary for the operation of the electrometer is derived from an external circuit by means of thermionic valves and it is therefore possible to secure accurate analyses of complex waves of small amplitude, satisfactory results being obtained with a root-mean-square value of 1 volt.

In the body of the paper a general description of the apparatus is given and experimental results are cited to show the degree of accuracy that may be expected, while in the Appendices a more detailed investigation is made into certain points concerning the theory of the method.

INTRODUCTION

In 1925 Prof. Miles Walker and his collaborators described a harmonic analyser depending for its operation on the interaction, in a dynamometer, between two currents of equal frequency, one of which was proportional to some harmonic in the wave to be analysed, while the other was derived from a resonant circuit which had been tuned to the frequency of the harmonic.[†]

Since 1925, considerable advances have been made in the design of valves and valve circuits, and the demands of the amateur wireless engineer have resulted in the commercial production of large numbers of "components"—inductances, capacitances, resistances, and the like—with which oscillating circuits of great variety may be composed. It is therefore considered that a description of an apparatus for analysis, in which such easily-procurable units are employed, may be of interest.

GENERAL

The method is very similar in principle to that employed by Prof. Miles Walker, except that the indicating instrument used is an electrometer and not a dynamometer.

When a symmetrical electrometer is connected heterostatically (see Fig. 1) and used with constant voltages the deflection is given by the equation

$$\theta = K(V_a - V_b)[2V_c - (V_a + V_b)]$$

where K is a constant and V_a, V_b, and V_c are the voltages of the two quadrants and the vane respectively.

Thus when $(V_a + V_b)$ is small the deflection is proportional to the difference of potential between A and B. The proviso in regard to the smallness of $(V_a + V_b)$ is, however, unnecessary if the quadrants A and B are joined by a resistance R, the centre point of which is earthed and connected to the vane through the source of potential V_c (see Fig. 2). V_a is now equal and opposite to V_b, and thus

$$\theta = 2KV_c(V_a - V_b)$$

We can say then that for a symmetrical electrometer[†] so connected the deflection is directly proportional to the voltage applied between A and B and that the proportionality depends upon the magnitude of V_c.

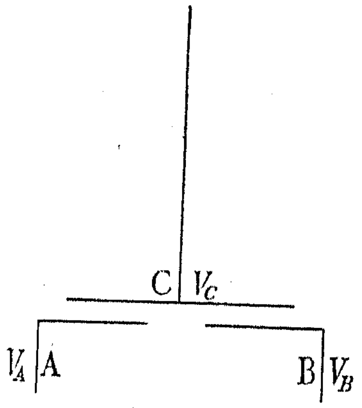

Fig. 1

If the potentials on vane and quadrants are sine functions of time, the deflecting torque is in general an alternating one.

Let $$V_c = V_1 \sin(n\omega t)$$

and $$(V_a - V_b) = V_2 \sin(m\omega t + \psi)$$

where $\omega = 2\pi \times$ frequency, n and m are integers, and ψ is a constant. Then the deflecting torque is proportional to

$$V_1V_2 \sin n\omega t \sin(m\omega t + \psi)$$

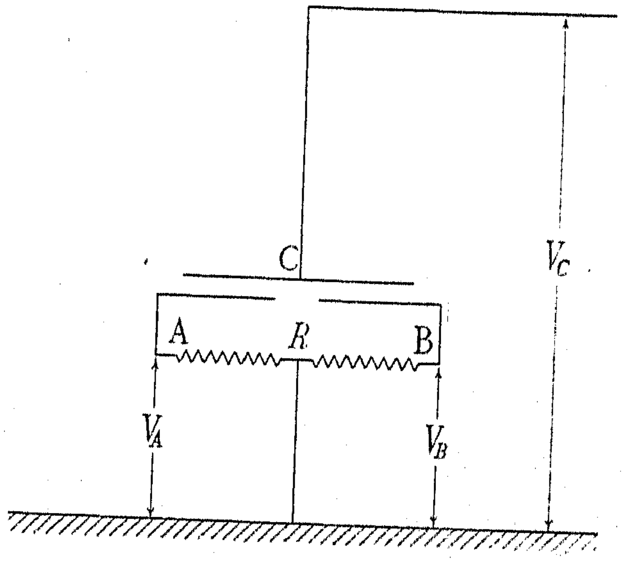

Fig. 2

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[*] King's College, University of Durham.

[†] See *Journal I.E.E.*, 1925, vol. 63, p. 69.

[†] See Appendix 1 for a discussion of the behaviour of an asymmetrical instrument.

that is, to

$$\frac{V_1V_2}{2}\left\{\cos\left[(m-n)\omega t+\psi\right]-\cos\left[(m+n)\omega t+\psi\right]\right\} \quad (1)$$

The resulting deflection will oscillate about the position of rest at two frequencies $(m-n)\omega/(2\pi)$ and $(m+n)\omega/(2\pi)$, and unless m and n are both small or nearly equal the inertia of the instrument will make the deflection small.

If, however, $m = n$, the deflecting torque is proportional to

$$V_1V_2\left[\cos\psi - \cos(2m\omega t+\psi)\right] \quad . \quad . \quad (2)$$

The first term represents a unidirectional torque which is directly proportional to the product of V_1 and V_2, while the second implies an alternating torque of frequency $m\omega/\pi$ the deflection due to which will in general be very small.

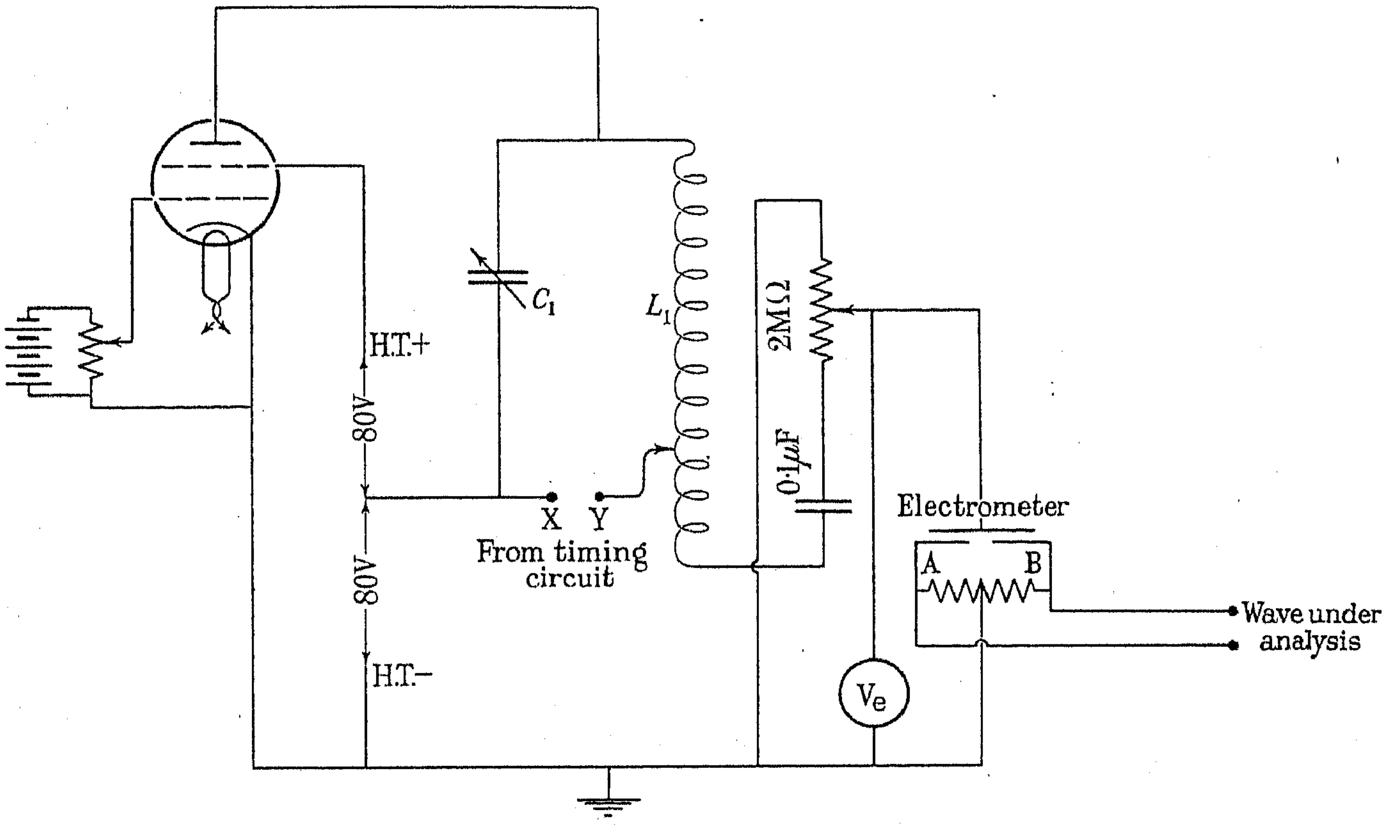

Fig. 3

In applying the electrometer to the analysis of a complex voltage wave, the wave to be analysed is made to energize the quadrants A and B while a sine wave of known amplitude and variable but known frequency is applied between the mid-point of R and the vane C.

Any complex harmonic function may be represented by the Fourier series

$$v_{ab} = V_1\sin(\omega t+\psi_1) + V_2\sin(2\omega t+\psi_2) + \ldots$$
$$+ V_m\sin(m\omega t+\psi_m) + V_n\sin(n\omega t+\psi_n)$$

If this be the voltage between the quadrants while the voltage on the vane is

$$v_c = V_c\sin(m\omega t+\alpha)$$

the deflecting torque will be proportional to the product of v_{ab} and v_c, the only component which can give a steady deflection being

$$V_cV_m\sin(m\omega t+\psi_m)\sin(m\omega t+\alpha)$$

for which the steady deflection is

$$\theta = KV_cV_m\cos(\psi_m-\alpha) \quad . \quad . \quad . \quad (3)$$

If $(\psi_m-\alpha) = 0$ we have $\theta = KV_cV_m$, and hence, if V_c and K are known, V_m is given by

$$V_m = \frac{\theta}{KV_c}$$

The development of the analyser depends then upon the possibility of producing a pure sine wave of voltage of known amplitude and frequency whose phase angle relative to some datum may be varied at will. This can be done conveniently by means of a dynatron oscillator.

If in a 4-electrode valve the potential of the grid nearest to the anode is higher than that of the anode, then secondary emission from the latter producing additional electrons attenuates or reinforces the stream from the filament and decreases or increases the anode current in proportion as its potential is raised or lowered. The valve thus acts as a negative resistance which is not dependent for its action on external coupling between the oscillating and the grid-filament circuit.

The arrangement of a satisfactory oscillator working on this principle is given in Fig. 3. The bias on the second grid, which is variable, is found to have a considerable influence on the frequency of oscillation and on the wave-form of the oscillating circuit, the best wave-form being obtained when this bias is just low enough to maintain oscillation. Since the current in the oscillating circuit is extremely small an iron-cored inductance may be used for L_1, while since an exact knowledge of its value is not necessary the capacitance C_1 may be composed of condenser units whose nominal value is correct to within 15 %. The iron-cored inductance may be arranged with variable tappings in order to increase the frequency range obtainable with a given maximum value of the variable condenser. It should be remarked, however, that, other things being equal, the lower the value of the inductance the purer will be the wave-form of the oscillator. If, further, the inductance is arranged as an auto-transformer, a large range of voltages may be obtained in the oscillator output. This output is applied between vane and quadrants of the electrometer, thus providing the source of voltage at known and variable frequency which can react on the harmonic components of the wave imposed on the quadrants A and B.

It remains to provide some datum from which the phase angles ψ and α may be measured. Instead of the neon lamps used by Miles Walker a gasfilled valve (e.g. a thyratron) is employed. For a given voltage between anode and cathode the valve is a non-conductor between these points until the negative bias on the grid has been reduced to a certain critical value. When this value is reached the valve becomes a conductor, the drop across which is small and practically independent of the value of the current flowing between the main electrodes. If this current is large a space charge is produced in the neighbourhood of the grid; and thus a subsequent increase of the negative grid bias, even if this carries it above the critical value, has no effect on the current between anode and cathode so long as the potential between these does not fall to zero. With small anode-currents, however, the grid appears to retain a measure of control and can arrest the anode current even though the anode voltage does not pass through zero.

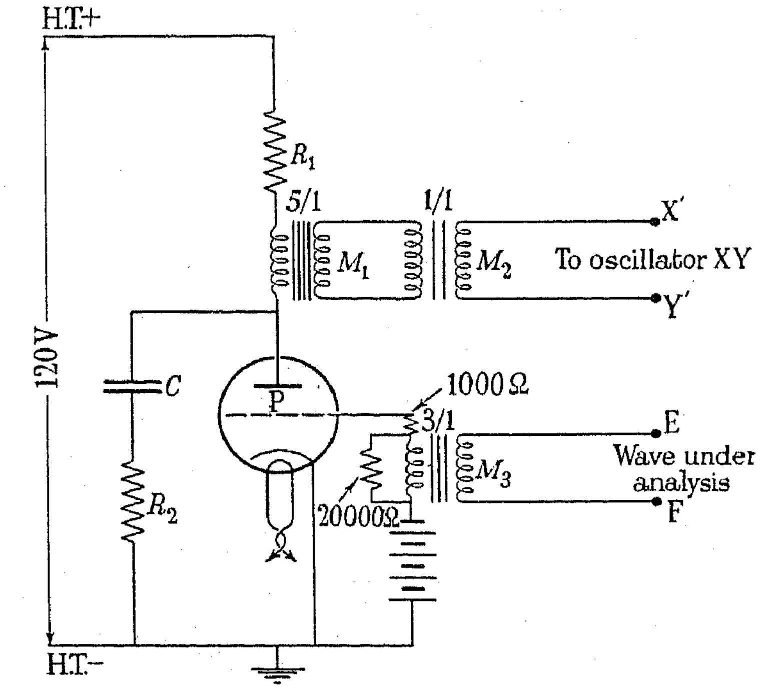

Fig. 4

If these characteristics of the valve are borne in mind it will be seen that the circuit of Fig. 4 will produce one sharp voltage-pulse at X′Y′ at a definite point in each complete period of an alternating potential applied to EF. This may be explained in the following manner. Let the potential applied between anode and cathode be 120 volts, and suppose that under this condition the minimum grid bias necessary to prevent the flow of current in the valve is pt_1 volts. This minimum will be reached at the points p and q in Fig. 5, where OB is the constant grid-bias upon which is superimposed the alternating potential supplied to the grid. During the time Ot_1 the condenser C will charge up through resistances R_1 and R_2 in series until the point p is reached. Here C will discharge impulsively through the resistance R_2 and the valve P. The mutual inductance M_1 will transfer a sharp pulse of e.m.f. to X′Y′. The valve will retain its conducting properties till some point on the voltage curve to the right of n is reached, where, if the valve current is small (as it will be under the voltage and resistance conditions of Fig. 4), the grid will regain control and the condenser will recharge in readiness for a second and similar cycle of operations at q.

If now the e.m.f. between X′ and Y′ be introduced into the oscillating circuit of Fig. 3 at XY, it will tend to drive this circuit and keep it in step with the alternating e.m.f. applied at EF. The phase relation of the current in the oscillating circuit and the pulse of e.m.f. introduced at XY will depend on the value of the variable capacitance C_1 in Fig. 3. The combination of the circuits of Figs. 3 and 4 thus provides not only a datum point on the wave applied at EF from which time may be measured but also a means of varying the phase of the dynatron oscillator e.m.f. relative to the applied wave. In other words, by suitable adjustment of L_1 or C_1 in the resonant circuit, $(\psi_m - \alpha)$ in equation (3) may be made equal to zero.

One further consideration remains to be discussed. The point on the applied wave at which the thyratron becomes conducting depends not only on the magnitude of the wave and of the grid bias but also on the anode potential. The introduction of the impulsive e.m.f. at XY implies a certain amount of reaction of the dynatron circuit upon the anode voltage of the thyratron; thus in order to preserve the stability of the impulse and a good wave-shape in the dynatron circuit a loose coupling M_2 is provided in series with M_1.

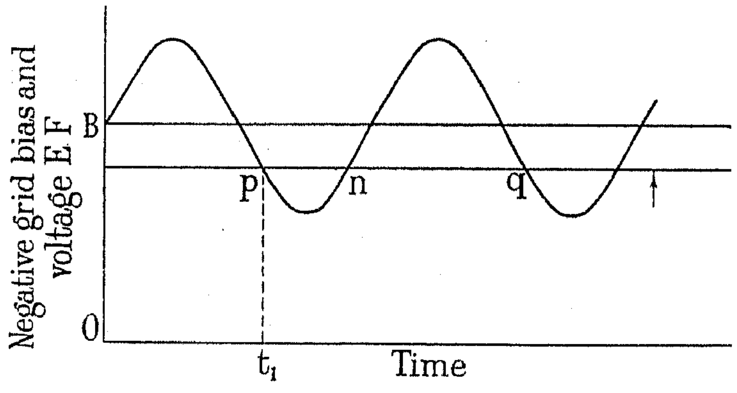

Fig. 5

The application of the complete apparatus to harmonic analysis may now be summarized in reference to Figs. 3 and 4. The wave to be analysed is applied to the quadrants A and B of the electrometer and to the grid and grid bias of the thyratron at E and F. The secondary of M_2 is connected into the oscillating circuit L_1C_1 of the dynatron. The mid-point of the resistance R joining A and B is connected to one end of the inductance L_1, while to an extension of L_1 is connected the vane of the electrometer, an electrostatic voltmeter being placed between the vane terminal and the mid-point of R. If the L_1C_1 circuit is now tuned, by adjustment of C_1, till it oscillates at the fundamental frequency of the voltage of supply, a deflection will appear on the electrometer. The magni-

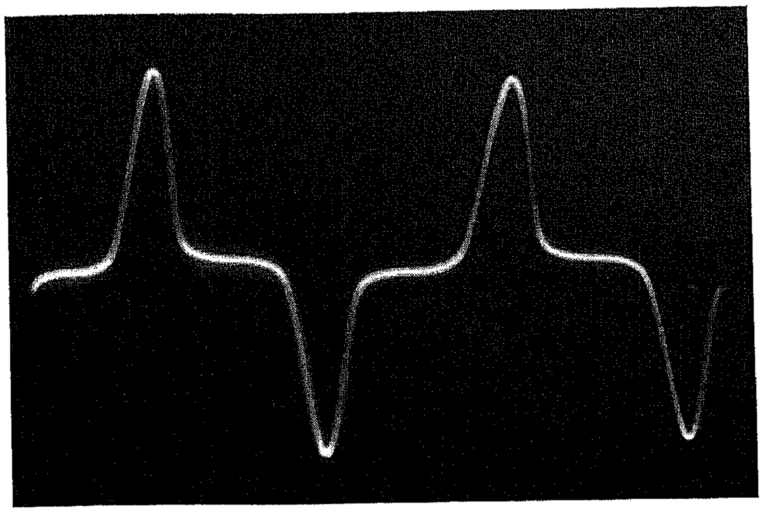

Fig. 7.—50-cycle wave from saturated choking coil (analysed in Table 1).

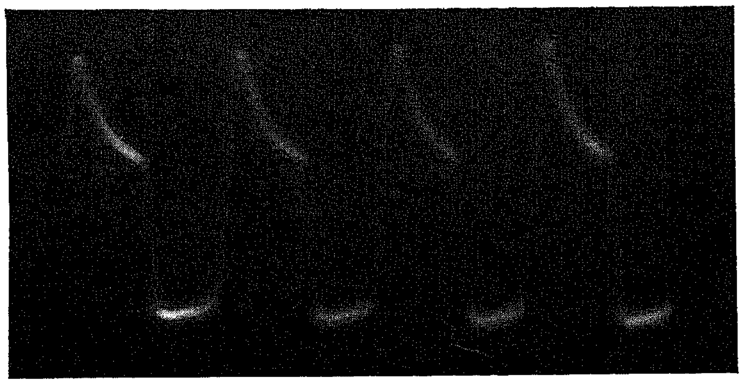

Fig. 8.—830-cycle wave (analysed in Table 2).

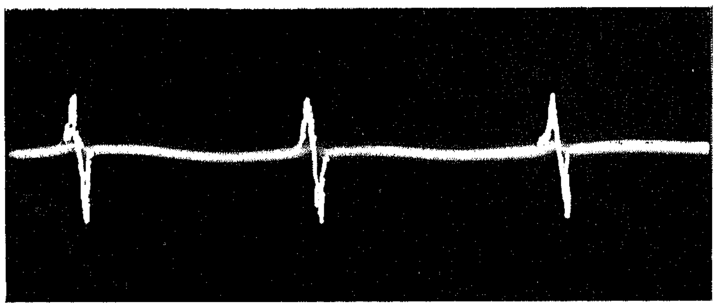

Fig. 9.—Thyratron impulse, magnified to show wave-form.

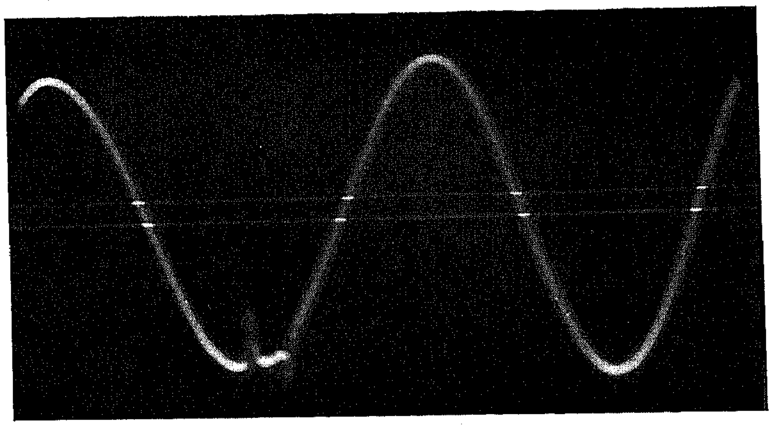

Fig. 10.—100-cycle analysing wave, showing thyratron impulse.

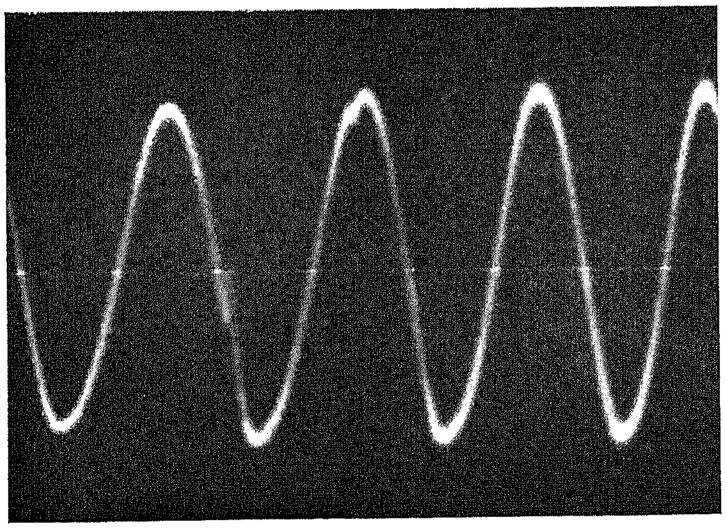

Fig. 11A.—250-cycle analysing wave, showing thyratron impulse.

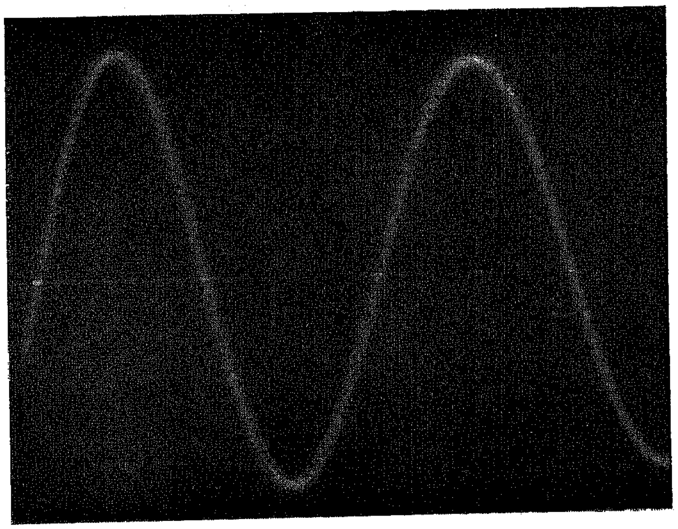

Fig. 11B.—Portion of 250-cycle analysing wave, showing wave-form.

tude of this deflection may be varied by a fine adjustment of C_1 until a maximum is obtained. The electrostatic voltmeter V_e is now read and the circuit tuned to oscillate at the 3rd harmonic of the fundamental, for which the above procedure is repeated. The 5th and higher harmonics are treated in a similar manner. It is an advantage during these tests to keep the reading of V_e constant, and this can be done by inserting a potentiometer between the inductance L_1 and the vane of the electrometer. If θ_1, θ_3, θ_5, etc., are the maximum deflections recorded by the electrometer for the fundamental, the 3rd, and the 5th harmonic respectively, we have the equations

$$\theta_1 = 2KV_eV_1$$
$$\theta_3 = 2KV_eV_3$$
$$\theta_5 = 2KV_eV_5$$

where V_1, V_3, V_5 are the r.m.s. values of the fundamental, the 3rd, and the 5th harmonic voltages.

It remains to determine the value of K. This may be done conveniently by applying direct voltages of from 0 to 4 volts to the quadrants A and B while a tapping on the H.T. battery is used to apply a voltage V_e between the vane and the mid-point of R. Keeping V_e constant, the voltage on the quadrants is varied and a curve obtained, which should be a straight line, between the deflection of the instrument and the quadrant voltage. The slope of this line gives the constant $2K$. Since this constant will depend on the value of V_e, the calibration should be carried out with the same value of V_e as was used when the vane was connected to the oscillator.

EXPERIMENTAL WORK

In analysing a wave the first step is to find the frequency of the fundamental by adjustment of inductance and capacitance in the oscillating circuit. This can be done by observing the behaviour of the electrometer while the adjustment is taking place, and watching for the slow swing which indicates that a component of the wave applied to the quadrants is nearly in phase with the potential supplied by the oscillator. The procedure may be expedited by connecting a pair of telephones through a valve across the oscillating circuit and listening for the beat between the oscillator wave and the impulse from the thyratron circuit (see Fig. 6). When synchronism is attained it is indicated by the cessation of the beat in the telephones and the appearance of a steady deflection on the electrometer. The grid bias of the dynatron is now adjusted, by increasing it, till sustained oscillation is just on the point of ceasing. The grid bias of the thyratron is adjusted till that valve is on the point of becoming non-conducting (the non-conducting condition is indicated by the disappearance of glow in the valve and the obliteration of the thyratron note in the telephones). The variable condenser is now adjusted till a maximum deflection is obtained on the electrometer, and this is recorded together with the reading of the electrostatic voltmeter. With this reading maintained, the quadrants are now disconnected from the supply and the zero reading observed. This completes the readings for the fundamental.

For the *n*th harmonic, the condenser setting for the fundamental is divided by n^2 and the condenser is set to this value without alteration of the dynatron grid bias. By fine capacitance adjustment the beat in the telephones is eliminated and then the grid-bias adjustments are made as before, and the system is retuned if necessary for maximum steady deflection (a vernier condenser of about 0·001 μF is very convenient for fine tuning). The zero is again checked by disconnecting the quadrants, and should be the same as that observed when measuring the fundamental if the reading of the electrostatic voltmeter has been kept constant.

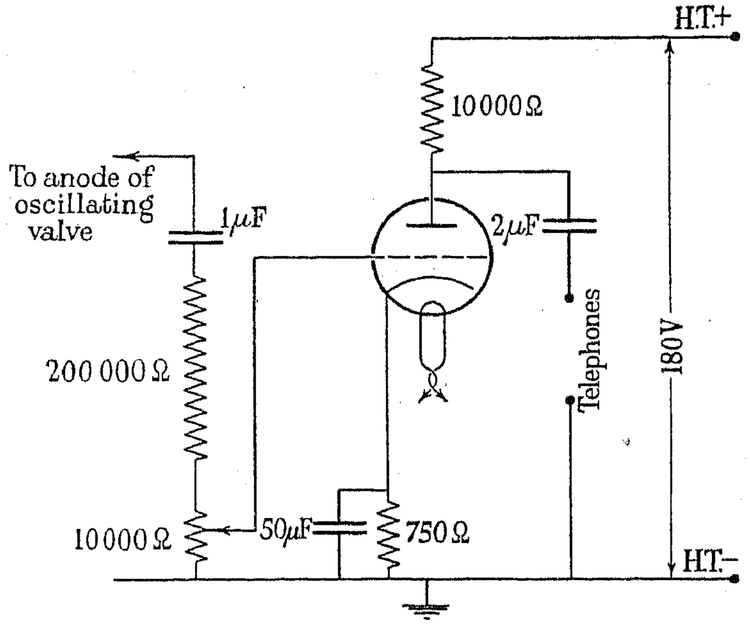

Fig. 6

EXPERIMENTAL RESULTS

Analysis of the wave shown in Fig. 7 (see Plate, facing page 304) was carried out with the help of the instrument as far as the 17th harmonic, the fundamental having a frequency of 50 cycles per sec. The wave represents the voltage across a resistance in series with a saturated iron-cored choking coil. A potential of 1 volt was tapped from this resistance and applied to the quadrants of the electrometer and the grid circuit of the thyratron. A trace of the wave was taken on a Cossor oscilloscope and analysed

Table 1

Number of harmonic	Percentage of fundamental	
	By selected ordinates	By analyser
Fundamental	100	100
3rd	64·0	64·0
5th	30·6	29·3
7th	10·5	11·65
9th	4·35	5·28
11th	3·57	4·1
13th	2·17	3·12
15th	1·75	1·84
17th	1·45	1·77

by the selected-ordinate method, using 18 ordinates in the half-wave. The comparative results are given in Table 1.

The oscillator potential on the vane of the electrometer was kept constant throughout at 55 volts; the deflection for the fundamental was 20·85 cm., and for the 17th harmonic 0·37 cm.

The voltage wave shown in Fig. 8 (see Plate) was obtained from the secondary of a transformer supplied, through a half-wave copper-oxide rectifier, from a high-frequency alternator, the fundamental frequency being 830 cycles per sec. This was applied to the analyser and gave the results shown in Table 2.

Table 2

Number of harmonic	By selected ordinates	By analyser
Fundamental	100	100
2nd harmonic	15	17
3rd harmonic	29	28·4

The selected-ordinate calculation was made from 6 ordinates in the half-wave.

It was found impossible with the existing oscillating circuit to proceed to frequencies higher than the 3rd harmonic of this wave (i.e. above 2 500 cycles per sec.), as the self-capacitance of the inductance was large; but a dynatron oscillator designed for the purpose could easily compass frequencies as high as 100 kc./sec. and might be used in the analysis of speech-frequency currents.

The time taken to obtain the analysis shown in Table 1 was about half an hour, representing an average of about 4 minutes per reading. This compares favourably with the time required for analysis with 18 selected ordinates. Thompson in his original paper* gives 70 minutes as the time required for the calculation, to which must, of course, be added the time required for enlarging the oscillograph record, erecting the 18 ordinates, and measuring them. Probably 2 hours would be a moderate estimate for the total time expended.

In making the analyses it was found that the thyratron circuit administered a sufficient impulse to the oscillator to keep the latter synchronized with the wave under analysis, even though the frequency of the latter varied somewhat. For instance, the wave whose components are given in Table 2 was obtained from a motor-generator set supplied from the 240-volt direct-current mains, and no special precautions were taken to maintain its speed exactly constant. Once the oscillator wave and the wave under analysis have been brought into step they tend to remain synchronized, and considerable variations may be made in the oscillator capacitance without disturbing this condition.

When the apparatus is first started up a certain amount of instability may occur, and persist, until a steady temperature state is reached in the valves. But once the steady state has been achieved satisfactory stability ensues.

PRACTICAL DETAILS

The particulars of the various circuits are as follows:—

Dynatron oscillator (Fig. 3).

Valve: Mazda AC. S2.

Grid bias: 1 to 4 volts, depending on value of inductance L_1.

Capacitance C_1: 1·11 μF, by steps of 0·001 μF, in parallel with a vernier condenser of 0·001 μF.

Inductance L_1: Iron-cored choking coil of 6 000 turns, tapped at intervals of 1 000 turns. Inductance per 1 000 turns = 0·8 H. Resistance per 1 000 turns = 78 ohms (average).

The 0·1 μF condenser in series with the 2-megohm potentiometer is introduced in order that the negative side of the H.T. may be earthed.

Impulse circuit (Fig. 4).

Valve: Osram G.T.1.

$R_1 = R_2 = 10\,000$ ohms. $C = 0\cdot1\ \mu$F.

M_1 intervalve transformer, ratio 5/1. H.T. inductance, 60 H.

M_2 microphone transformer, with open iron circuit, ratio 1/1.

M_3 intervalve transformer, ratio 3/1.

Grid bias 4 to 8 volts, depending on the magnitude of the wave under analysis.

Current taken by impulse circuit from circuit of wave under analysis at 1 volt = 0·52 mA.

Telephone circuit (Fig. 6).

Valve: Brimar PA1 (Standard Telephones and Cables).
Telephones: Brown Type A.2. Resistance: 2 000 ohms.

Electrometer.

Dolezalek, with phosphor-bronze suspension.

Sensitivity with 50 volts on needle, about 10 cm. per (volt)^2

Resistance across quadrants 100 000 ohms, earthed at mid-point.

Current taken from circuit of wave under analysis at 1 volt = 0·01 mA.

In order that the electrometer should give rapid indications of applied potentials a small paddle was fitted to the vane and allowed to dip into an oil vessel which was accommodated between the insulating supports carrying the quadrants. The viscosity of the oil was adjusted until the instrument was very nearly aperiodic. This arrangement greatly facilitates the taking of the readings.

CONCLUSION

The author wishes to thank Prof. E. W. Marchant, Past-President, for helpful criticism and advice given during the earlier stages of the development of the analyser and for permission to use apparatus in the Laboratories of Applied Electricity, University of Liverpool. He also wishes to record his grateful appreciation of the assistance which was given him by Messrs. A. S. Hill, J. S. F. Rodrigo, and J. S. Wilson, when students in the University of Liverpool; and by Mr. H. H. Monkhouse in King's College, University of Durham.

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* *Electrician*, 1905, vol. 55, p. 79.

APPENDIX 1

Electrometer Characteristics

The general expression for the deflection of the electrometer is

$$\theta = \left[K_1(V_c - V_a)^2 - K_2(V_c - V_b)^2\right] \quad . \quad (1a)$$

where V_c is the vane voltage and V_a and V_b are the voltages of the quadrants.

If the instrument is symmetrical, then $K_1 = K_2 = K$ (say), and

$$\theta = K(V_a - V_b)\left[2V_c - (V_a + V_b)\right]$$

If the instrument is asymmetrical, let $K_1 = K_2 + \delta$. Then

$$\theta = (V_a - V_b)\left\{2K_2V_c - K_2(V_a + V_b) + \left[\frac{(V_c - V_a)^2}{(V_a - V_b)}\right]\delta\right\}$$

By earthing the mid-point of the resistance joining the quadrants, we have $V_a = -V_b$. Then

$$\theta = (V_a - V_b)\left[2K_2V_c + \frac{(V_c - V_a)^2}{V_a - V_b}\delta\right] \quad . \quad (2a)$$

If the quadrants are disconnected from the source of supply, then $V_a = V_b = 0$ and $\theta = \delta(V_c - V_a)$ if V_c is maintained as the potential of the vane. By altering the level of the instrument the deflection may now be brought to zero, and the instrument will then behave as if symmetrical, since δ has been reduced to zero. For this condition, then, with the mid-point of the quadrant resistance tapped,

$$\theta = K(V_a - V_b)(2V_c)$$

Returning to the case of the asymmetrical instrument, the deflection with vane and quadrants energized is given by equation (2*a*); if the zero θ_0 is taken with the quadrants disconnected, then

$$\theta_0 = \delta V_c^2$$

and the difference

$$\theta - \theta_0 = (V_a - V_b)\left[2K_2V_c - \frac{V_a(2V_c - V_a)}{V_a - V_b}\delta\right]$$

whereas if $K = K_2$ the true reading for a symmetrical instrument will be

$$\theta - \theta_0 = K_2(V_a - V_b)(2V_c)$$

The magnitude of the error term may be assessed in reference to the electrometer referred to in the paper.

With a p.d. of 1 volt across the quadrants and a vane potential of 50 volts, a deflection of 10 cm. was obtained. Thus, in terms of scale deflection, $K_2 = \frac{1}{10}$ cm./(volt)^2 If the asymmetry is so large as to give 5 cm. deflection with $V_a = V_b = 0$ and 50 volts on the vane, then $\delta = 5/(50)^2 = 1/500$ cm./(volt)^2 Therefore, with $V_a - V_b = 1$ and $V_a = -V_b$,

$$\theta - \theta_0 = 10 - 0{\cdot}0995$$

as compared with 10 for the symmetrical instrument, or an error of 1 %.

APPENDIX 2

Computation of Errors

In computing the accuracy that may be expected from the analyser it is necessary to consider first the behaviour of the electrometer.*

The accuracy of the analyser also depends directly upon the degree of purity of the analysing wave applied to the vane.

When the thyratron circuit is energized a sharp voltage-pulse is imposed on the oscillating circuit. This is shown in Fig. 9 (see Plate), which represents the voltage of the secondary of the loose coupling M_2 when the H.T. battery of the dynatron circuit has been removed. When the dynatron is in operation the impulse combines with the normal oscillation to give such curves as those shown in Fig. 10 for the 2nd harmonic and in Figs. 11A and 11B for the 5th harmonic.

The magnitude of the impurity introduced by the timing impulse is difficult to assess analytically, but assuming the impulse to be a heavily damped oscillation given by

$$v_u = Ue^{-\lambda(t-\alpha)}\cos(n\omega t + \alpha)$$

of a frequency which is high compared with that of the fundamental of the wave under analysis (α = a constant, λ = damping coefficient), it may be shown† that if U is its maximum amplitude and n its frequency, counting the fundamental frequency of the wave under analysis as unity, then its component of frequency m will be

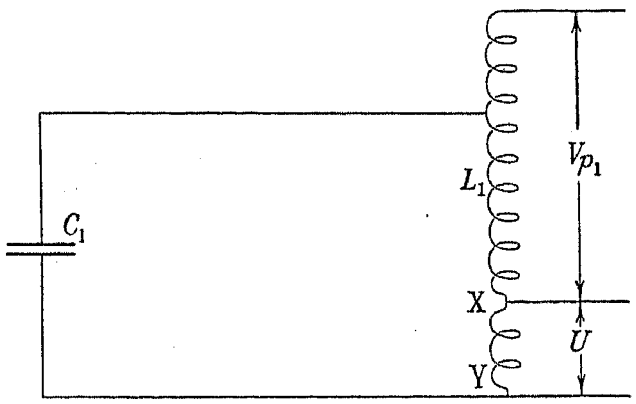

Fig. 12

The inductance between X and Y is very small compared with that of L_1.

$$U_m = \frac{U}{2\pi}(a^2 + b^2)$$

where

$$a = \frac{\lambda}{\omega}\left[\frac{1}{(\lambda/\omega)^2 + (m-n)^2} + \frac{1}{(\lambda/\omega)^2 + (m+n)^2}\right]$$

$$b = \left[\frac{m-n}{(\lambda/\omega)^2 + (m-n)^2} + \frac{m+n}{(\lambda/\omega)^2 + (m+n)^2}\right]$$

and $\omega = 2\pi \times$ fundamental frequency.

This expression is only applicable for $\lambda/\omega > 0{\cdot}5$. Measurement of Fig. 9 shows that $n = 10$; and λ/ω, assuming α is zero, may be taken as $2\,500/(100\pi) = 8{\cdot}0$; which gives the fundamental component of U as $U_1 = 0{\cdot}0155U$ at a frequency of 50 cycles per sec. This potential is introduced into the oscillating circuit (see Fig. 12).

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* See Appendix 1.

† See Appendix 3.

The current circulating due to U_1 will be

$$I_{u_1} = \frac{U_1}{\left[R^2 + \left(L\omega - \frac{1}{c\omega}\right)^2\right]^{\frac{1}{2}}}$$

and the voltage across the inductance due to this current will be

$$V_{u_1} = \frac{U_1 L\omega K'}{\left[R^2 + \left(L\omega - \frac{1}{c\omega}\right)^2\right]^{\frac{1}{2}}}$$

where K' is a constant depending on the tapping used on the inductance, and where $\omega = 100\pi$ for the 50-cycle wave. If the circuit is tuned for the 2nd harmonic, then $2L\omega = 1/(2c\omega)$ and

$$V_{u_1} = \frac{U_1 L\omega K'}{(R^2 + 9L^2\omega^2)^{\frac{1}{2}}}$$

Measurement of the oscillograph records again shows that, if V is the maximum value of the voltage generated by the oscillator, then $U = V/8$: thus when working on 4 sections of the oscillator inductance, i.e. with $L = 14 \cdot 8$ henrys and $R = 312$ ohms, and with the circuit tuned to the 2nd harmonic of the 50-cycle wave,

$$V_{u_1} = 0 \cdot 00065 V \text{ (nearly)}$$

That is to say, the analysing wave for the 2nd harmonic will contain a $0 \cdot 065$ % component of the fundamental frequency.

With higher frequencies the accuracy is not so good. When a wave of frequency 800 cycles per sec. is being analysed the frequency of the impulse wave from the thyratron changes somewhat, increasing from 500 cycles per sec. (corresponding to $n = 10$ in the previous paragraph) to about 800 cycles per sec. It is thus of nearly the same frequency as the fundamental of the wave to be analysed. Taking $e^{-\lambda t}$ as equal to $0 \cdot 007$ when $t = 1/800$ sec., we have $\lambda t = 5$ and thus $\lambda = 4\,000$. For $\omega = 2\pi \times 800 = 5\,000$ (say), we have $\lambda/\omega = 0 \cdot 8$. Introducing this value into the expressions for a and b, and putting $m = n$, we have

$$U_1 = \frac{U}{2\pi}(1 \cdot 4) = 0 \cdot 223 U$$

This fundamental component, applied to a circuit tuned for the 2nd harmonic, will give

$$V_{u_1} = 0 \cdot 009 V$$

or an impurity of $0 \cdot 9$ %.

The wave-form of the oscillation produced by the dynatron itself also exercises an influence on the accuracy which may be expected. The highest purity of the wave is associated, as has been said, with high values of the grid bias, and analyses of the wave-form of the oscillator show that the maximum impurity does not exceed about 4 % for frequencies from the 50-cycle fundamental to the 17th harmonic. The predominating harmonic in the oscillator wave was found in every case to be the 2nd, and its presence is therefore unimportant when analyses of generator waves are undertaken. Investigation of the wave-forms at higher frequencies, using air-cored inductances, showed that sine waves of even greater purity could be obtained.

APPENDIX 3

Error introduced by thyratron impulse

Let the voltage impulse be represented by

$$v_t = U e^{-\lambda(t-\alpha)} \cos n\omega(t - \alpha)$$

Now let v_t be expressed as a Fourier series, in the form

$$\begin{aligned} v_t = \frac{a_0}{2} &+ (a_1 \cos \omega t + b_1 \sin \omega t) \\ &+ (a_2 \cos 2\omega t + b_2 \sin 2\omega t) + \ldots \\ &+ (a_m \cos m\omega t + b_m \sin 2\omega t) \end{aligned}$$

Multiplying each equation by $\cos(m\omega t)$, and integrating, we have

$$a_m = \frac{U}{2\pi}\int_0^{2\pi} e^{-\lambda(t-\alpha)} \cos n\omega(t - \alpha) \cos m\omega t d(\omega t)$$

as the value of the coefficient of the cosine term of the mth harmonic in the impulse.

If λ is large, i.e. if $e^{-\lambda(t-\alpha)}$ is negligible when $\omega t = 2\pi$, this becomes

$$a_m = \frac{U}{2\pi}[\mu_m \cos(m\omega\alpha) - \nu_m \sin(m\omega\alpha)]$$

where

$$\mu_m = \frac{\lambda}{\omega}\left[\frac{1}{(\lambda/\omega)^2 + (m-n)^2} + \frac{1}{(\lambda/\omega)^2 + (m+n)^2}\right]$$

$$\nu_m = \left[\frac{m-n}{(\lambda/\omega)^2 + (m-n)^2} + \frac{m+n}{(\lambda/\omega)^2 + (m+n)^2}\right]$$

Similarly we obtain

$$b_m = \frac{U}{2\pi}[\mu_m \sin(m\omega\alpha) + \nu_m \cos(m\omega\alpha)]$$

The peak value of the mth harmonic in the impulse is

$$\begin{aligned} U_m &= (a_m^2 + b_m^2)^{\frac{1}{2}} \\ &= \frac{U}{2\pi}(\mu_m^2 + \nu_m^2)^{\frac{1}{2}} \end{aligned}$$

Putting $m = n$, we have, as the component of frequency n,

$$U_n = \frac{U\omega}{\pi\lambda}\left[\frac{(\lambda/\omega)^2 + n^2}{(\lambda/\omega)^2 + 4n^2}\right]^{\frac{1}{2}}$$

[The discussion on this paper will be found on page 309.]

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 3RD FEBRUARY, 1939, ON THE PAPERS BY DR. H. M. BARLOW (SEE PAGE 295) AND PROF. J. C. PRESCOTT (SEE PAGE 302).

Mr. E. B. Hunter: I shall confine my remarks to Dr. Barlow's paper.

Mention is made in the paper of fires due to neon-sign installations, and I have had the opportunity from time to time of investigating such fires. In every case where evidence has been available it has pointed to the fact that the fire was due to leakage from the high-voltage circuit to earth.

Dr. Barlow's protective device is very sensitive to small currents, and it would be interesting to know whether any tests have been made to find out whether it is too sensitive under normal conditions of service. For example, neon signs are often exposed to rain. If the glass of the tube gets damp near the electrode is this sufficient to bring the trip gear into action owing to surface leakage, and thus to open the circuit when no danger may exist?

It is very desirable that no undue cost should be put on to installation work, and as each transformer has to be equipped individually with one of these safety devices it would be interesting to know whether the percentage cost of the installation is thereby largely increased.

If the author touches the terminals of the sign when protected by the device, does he feel anything in the nature of a shock? An electrician working on a sign is usually at a high level, and even if he only felt a small shock it might cause him to lose his balance and be killed by the fall.

Dr. S. Whitehead: I shall confine my contribution to Prof. Prescott's paper.

The tuned-circuit type of analyser can be used for a large variety of purposes and it can also be made very sensitive, but it suffers from the disadvantage that in order to reach the highest selectivity it is necessary to multiply the number of tuned circuits, unless one uses a form of negative resistance arrangement to compensate for coil losses, which is somewhat difficult to realize in practice.

As regards the frequency-changer type, in my own laboratory we use a low intermediate frequency of about 17 cycles per sec., but commercially a high intermediate frequency—well above the range which is to be analysed—is more common. The frequency-changer type of analyser is more or less limited to straightforward wave analysis, and its selectivity, although high, is limited by the stability of its local oscillator, which may require some care. On the other hand, this type is extremely rapid in action; in fact, with a good instrument and expert observers, the greater amount of time is taken in recording the readings, while the sensitivity is theoretically only limited by circuit and valve noise.

Those analysers which depend upon the reaction of an instrument have much more pronounced advantages and correspondingly pronounced disadvantages, and are of a more specialized nature. As regards the advantages, the selectivity is only limited by the synchronism of the synchronous-motor contactor in the dynamometer instrument or by the synchronism of the controlled oscillator in the author's instrument. The accuracy also is as great as one could wish, being limited only by the electrometer or dynamometer and the voltmeter or milliammeter for the analysing wave. Such difficulties as balance and impedance need not arise, particularly with the present instrument, which can be of very high impedance and isolated from earth. As regards the disadvantages, the sensitivity of these analysers is low; they will only measure harmonic overtones and they are not portable. Lastly, these instruments are slow in taking readings and there is considerable prejudice against electrometers, particularly among younger engineers, on account of the trouble encountered in making the initial adjustments.

My own conclusion is that the dynamometer and electrostatic analysers are specialized instruments preeminently fitted for the testing of power plant in the laboratory or test bay; but so important an application should, I feel, yield adequate scope for these instruments.

Captain C. Higgins: I shall deal exclusively with the paper by Dr. Barlow.

There are two circuits used in the operation of neon signs which the author does not mention. One employs a large transformer with high-voltage chokes for operating a number of neon-sign circuits; and the other has resistances in place of chokes. These present considerable obstacles to the economical application of any of the safety devices mentioned in the paper.

In the past few years The Institution has prepared a number of excellent regulations regarding the installation of luminous discharge-tube signs, and I claim that if these regulations are properly adhered to there is no necessity for any other safety device. I deprecate the author's suggestion that " When a protective device of this kind is employed special fire-resisting materials for the background and mounting of discharge tubes become unnecessary." It is rather like suggesting that because the powder in a powder magazine is contained in barrels therefore you may smoke, forgetting, of course, that sometimes a barrel may come open.

The circuit arrangements shown in Figs. 5, 7, and 8, do not comply with the requirements laid down in the I.E.E. Wiring Regulations.

Finally, I would say that if we are going to use this type of apparatus—and I think it is desirable to consider it from the point of view of safety—there are in my opinion four essentials. The first is that on the development of a fault which operates the safety switch, the switch should remain open; in other words, it should have to be reset, so that the fault must be cleared before the sign comes into operation again. The second is that the switch should comply with the I.E.E. Wiring Regulations. The third is that the switch should be of such a design that it can be put into a circuit without modification of the transformer. The fourth is that some definite figure of leakage should be decided upon above which the switch will operate. We have to decide at what point we are going to bring the safety device into operation, because on a very wet day the leakage is sometimes as high as 10 mA outside the tube. Such a leakage is perfectly safe, and allows the sign to continue in operation.

Mr. R. O. Carter: I propose to confine my remarks to the paper by Prof. Prescott.

I should like first to refer to the sources of error which are dealt with in Appendix 2 of the paper. I agree that the accuracy of measurement depends upon the degree of purity of the analysing wave which is applied to the electrometer. This will depend to a large extent on the amplitude applied to the synchronizing pulse, and it is therefore desirable to operate the oscillator with the minimum possible amplitude of this synchronizing pulse from the thyratron. In order to bring the analysing wave into phase with the component to be measured the author in effect detunes the oscillatory circuit to the necessary amount. If this could be avoided it is probable that a smaller synchronizing pulse would suffice to maintain the oscillation in synchronism with the component to be measured. In this case the peak value of the wave would always coincide with the synchronizing pulse, and the minimum possible synchronizing pulse could be used. If this is done the quantity cos $(\psi_m-\alpha)$ in equation (3) will no longer be equal to unity. However, by feeding the output of the oscillator to a phase-splitting device, two measurements, one of $KV_cV_m \cos(\psi_m-\alpha)$ and the other of $KV_cV_m \sin(\psi_m - \alpha)$, can be taken, from which the value of KV_cV_m can be calculated.

If further by this method it is possible to ensure that the synchronizing pulse accurately coincides with the peak value of the component which is to be measured, one will be able from these two values to compute the phase of the component relative to the fundamental frequency of the wave, and thus obtain the phases of all components as well as their amplitudes.

Dr. Whitehead has already compared this method with the heterodyne method now in common use, and I agree with him that that type of instrument is more suited to a large number of rapid measurements. For instance, I think the results given in Table 1 of the paper could probably be obtained in 10 minutes with such an instrument, as compared with the half hour taken by the author's analyser.

Mr. S. J. Patmore: I am rather surprised at the large difference between the number of fires alleged to be due to discharge tubes which occurred in London in 1936—Dr. Barlow mentioned this as being 45—and in 1937, when the number was said to be 61. I think that while the 1937 figure seems so much higher than the 1936 figure, the number of new signs installed in this period in the London area has been so tremendous that the proportion of fire risks is not nearly so high as these figures would indicate.

Mr. R. I. Bagnall: Dr. Barlow's protective device is a distinct advance on some of the systems which are described in the earlier part of his paper, and which can not be regarded as altogether satisfactory. There is one point about it which is, however, rather alarming. It seems to call for division of the earth wire, since separate ends at earth potential from each half of the high-voltage winding must be brought to the device. This would seem to limit the use of the device to new transformers specially designed for the purpose, and one rather wishes that the effect could be obtained by dealing with the primary circuit only. Has Dr. Barlow considered trying to do so by means of the variation in power factor which occurs under various conditions?

Mr. R. D. Moss: I think that the cost of Dr. Barlow's protective equipment may be a deterrent to the installation of such a device unless it becomes compulsory under any regulations.

The number of fires is small in comparison with the number of signs installed, and the fires are usually confined to the signs themselves; they do not spread from the sign to the building.

With regard to shock from signs, I can only remember one fatal accident in London since luminous discharge-tube signs were first installed, and that occurred when they were in their infancy.

Mr. C. E. Mills: I have two questions to ask in connection with Dr. Barlow's paper. First, do fluctuations in the primary voltage due to poor regulation of the supply affect the sensitivity of the relay? Secondly, if a person who is insulated from earth touches both the electrodes, will he not then be in danger of receiving a shock?

Mr. F. E. J. Ockenden: There is in Dr. Barlow's arrangement one point which seems to me to constitute a serious objection: it can be quite plainly seen in Fig. 7. In the event of a break in the winding of either of the relay coils the full potential of the transformer will be across the defective winding, and either continuous sparking will occur, which will burn out the relay completely, or the operator will get a serious shock. I would suggest as a possible alternative that if the windings, instead of being connected directly to the transformer, were connected by rectifiers, then in the event of the winding breaking the rectifier would convey the current through the main transformer.

Prof. E. W. Marchant (*communicated*): The method which Prof. Prescott describes is one which involves no appreciable expenditure of power for its application and is therefore adaptable to the analysis of very small currents such as those obtained from a microphone or other light-current equipment. The equipment required for the analysis is very simple, and when one compares an analyser of this kind with the mechanical harmonic analysers which have been used for many years, the advantages of the electrical method become increasingly apparent. The only part of the apparatus which is delicate and requires careful manipulation is the electrometer, and I hope that Prof. Prescott may be able to simplify its design still further. There is no limit to the frequency of the harmonics which can be detected, until one reaches frequencies where the charging currents for the quadrants become appreciable in magnitude, and this only happens at the higher radio frequencies. The analyser represents a very great advance on the one which was described by Prof. Miles Walker[*] and his associates, in that the indicating instrument takes so little power and also enables a higher frequency of harmonic to be detected without appreciable error. In the dynamometer type of analyser the inductance of the high-resistance circuit which supplies the moving coil of the dynamometer requires very careful design if the phase of the currents due to the harmonics is not to be appreciably changed; whereas, in this case, the phase of the voltage due to the harmonics is exactly right. The production of the auxiliary voltage by which the value of the harmonics is determined by means of a dynatron oscillator is a new application of this type of oscillator. Dr. Houldin has shown that the wave-shape of voltage given by this oscillator does not approximate closely to a pure sine curve, except under very carefully specified conditions. If a harmonic is present in the auxiliary oscillation it will, of course, react with a harmonic of corresponding frequency in the wave which is being analysed. Prof. Prescott's apparatus should be of the greatest practical utility in connection with light-current electrical engineering.

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[*] *Journal I.E.E.*, 1925, vol. 63, p. 69.

Major T. H. Solomon (*communicated*): On page 296 Dr. Barlow states that " The effects of electric shock on the human body vary widely, but it is generally agreed that current is the principal factor determining the intensity and nature of the shock." This statement appears to me misleading, as it is the voltage to earth which determines the current through the body of any person who comes into contact with a live or leaky conductor. Thus if a person touches a point on a system where there is a leakage of 15 milliamp., his body forms a path to earth in parallel with the leakage path, and the current through his body will depend on the voltage to earth, not on the current through the leakage path.

Dr. Barlow refers to the fact that according to B.S.S. No. 559—1938 one point of the secondary winding of a luminous discharge-tube transformer must be earthed, yet in the device he describes in Fig. 7 there is no earth connection on the secondary winding itself. Thus the device, as it stands, does not comply with Regulation 804(C) in the I.E.E. Wiring Regulations or with British Standard Specification No. 559—1938, Part 2, Clause 22(*c*).

THE AUTHORS' REPLIES TO THE DISCUSSION

Dr. H. M. Barlow (*in reply*): Mr. Hunter refers to the sensitivity of my protective device to earth-leakage faults. The sensitivity is such that any fault on the circuit sufficient to cause a pronounced flicker or a permanent interruption of the electric discharge through the tube will bring the relay into action. Leakage over the surface of the glass tube near an electrode when exposed to rain is not as a rule large enough either to be a source of danger or to operate the protective device. On the other hand, I submit that a discharge tube which flickers in consequence of overload on the transformer, whatever the cause, should never be permitted to continue in operation. Not only is this flickering an indication of a fault on the circuit which is likely to start a fire if allowed to persist, but it also produces very serious interference with wireless receivers, television, and telephone apparatus. Moreover, experience has shown that a transformer supplying a flickering tube will sooner or later break down. Flashing the tube by periodic interruption of the primary circuit to the transformer is, of course, quite a different matter.

On a given discharge-tube circuit, the leakage which the protective device will tolerate without coming into action depends upon the normal conditions of load on the transformer. If the transformer is loaded up to the hilt, so that the discharge tube will only just strike, then a very small additional current taken from the secondary to feed an earth fault will immediately cause flickering or prevent the tube from striking altogether should the voltage at the terminals become insufficient to produce the necessary ionization. In practice, economic considerations require that the length of tube operated by a transformer should be such as to approach the flicker point, and the protective device therefore becomes correspondingly sensitive. In touching the terminals of the discharge tube to demonstrate the protection afforded against electric shock I felt only a momentary pricking sensation, not sufficient to cause any discomfort. As the threshold of decontrol corresponds to a current of about 15 milliamp. and as the protective device on a heavily loaded circuit will operate with leakage currents as small as 3 milliamp., a good margin of safety is provided.

The apparatus shown costs about £1. This is, of course, a substantial addition to the cost of a transformer but it does not add much to the cost of the installation as a whole, especially when one takes into consideration the economies which the protective device makes permissible in the use of fire-resisting materials for the construction of the sign. A simpler and much cheaper type of relay has now been developed. The cost of this relay, manufactured in large numbers, should not be more than about half that of the earlier design.

Captain Higgins draws attention to the use of choking coils or resistances in series with the discharge tube, instead of providing the transformer with a high leakage reactance. This arrangement is, I understand, unusual, but it does not preclude the use of the protective device. All that is required is a relay in each discharge-tube circuit, the voltage-regulation characteristics of which are the same as for the ordinary single-circuit transformer.

The regulations prepared by The Institution governing the installation of luminous discharge-tube signs are excellent so far as they go, but in my opinion they are at present incomplete. As was pointed out in the paper, overload protection on the primary circuit of the transformer is quite powerless to deal with faults occurring on the discharge-tube circuit, and the regulations should therefore have an additional clause requiring protection of the high-voltage circuit. This might be done by specifying a maximum leakage current of, say, 10 milliamp., above which the transformer must be automatically disconnected from the supply. Furthermore, the protective device should always operate to interrupt the primary circuit when an open-circuit occurs on the secondary. The existing regulations governing the choice of materials and methods of construction for luminous discharge-tube installations are a valuable and necessary guide to those concerned in this work, but in view of the very considerable number of fires and accidents for which neon-sign installations are still responsible it is manifestly unjustifiable to say that no further safety precautions are necessary. It is not consistent to employ fault protection on the primary circuit of a neon transformer and at the same time to maintain that no corresponding protection is required on the secondary circuit, where, in fact, the danger is much greater. My suggestion that the use of this protective device would enable expensive fire-resisting materials for the background and mounting of neon signs to be legitimately dispensed with, is, I think, quite reasonable. If the protective device removes the cause of such fires by ensuring that the operation of the sign is impossible under fault conditions, there is no object in providing materials to withstand the severe conditions of such faults. The materials to which I refer, as, for example, teak facias, are employed largely to prevent fire, not to prevent leakage. In Captain Higgins's analogy of the powder magazine, it is true that a barrel may come open but the protective device prevents any serious leakage of the powder.

Although the I.E.E. Wiring Regulations and B.S.S. No. 559—1938 state that one point of the secondary winding of a luminous discharge-tube transformer should be earthed, I submit that in extending the secondary circuit through the relay coil before earthing it there is no departure from the spirit of these regulations, which were drafted before any such protective system was envisaged. Electrically there is no material difference, since the p.d. across the relay coil is relatively very small, and the apparatus would normally be included in the same earthed metal case as the transformer. Major Solomon also refers to this matter, and I think he may not have realized that the relay and transformer together form a single unit. Any technical breach of the regulations which the use of this protective system may involve can easily be remedied when these regulations are revised.

Mr. Ockenden is concerned about the effect of a break in the winding of either of the relay coils. This would cause an interruption of the secondary circuit and immediately bring the relay into operation, so that no damage could be done. Such a fault is more likely to occur on the secondary winding of the transformer itself, since the voltage is so much higher, but the relay would again give complete protection. Mr. Ockenden's suggestion that the relay coils should be fed through rectifiers is therefore an unnecessary complication, and, incidentally, a costly one.

Captain Higgins lays down four points in connection with the design of a protective device which he regards as essentials. There is no difficulty in providing a type of switch which will remain open until reset after the relay has been operated, but the arrangement described in the paper has one very important advantage, that of remote control. Many neon-sign transformers are placed in most inaccessible positions, and the resetting of the accompanying relay then becomes a difficult matter. If a fault has not been cleared before the sign is switched into service again, the protective device operates immediately and the discharge tube does not have time to strike.

Captain Higgins's second point has already been dealt with.

The third point bears on a question raised by Mr. Bagnall. The modification of the transformer necessary to fit this protective device is never more than a very minor one. In the usual type of transformer employed in this country it is necessary to bring out insulated wires from the centre point of the secondary winding. When the transformer has a secondary winding of which one end is earthed, or when two independent secondary windings each earthed at one end are employed (as in the American centre-balanced transformer), no modification is necessary. In this case the relay coil is connected between earth and the low-potential end of the discharge tube.

With regard to the last point made by Captain Higgins, I suggest that 10 milliamp. should be the outside limit of the allowable leakage current.

Mr. Patmore and Mr. Moss both refer to the number of fires attributed to neon signs in London. The figures given are perhaps not so alarming as might have been expected, but I have recently received some statistics of similar fires in a large provincial area, showing that of the total number attributed to electrical installations in general, more than one-third were due to neon signs. This is a clear indication of the seriousness of the present position.

The suggestion made by Mr. Bagnall that use might be made of variations in the power factor of the supply to a discharge-tube installation to operate protective apparatus is, I think, effectively the same idea as that embodied in the device described in the paper, wherein the relay is controlled by the flux distribution in the transformer core.

Replying to Mr. Mills's first question, the sensitivity of the protective device is independent of voltage regulation on the primary supply except so far as the fluctuations of input voltage affect the output characteristic of the transformer. In answer to his second question I would say that although it is true that a person insulated from earth and touching the two electrodes of the discharge tube would not operate the protective device and therefore might receive a bad shock, there is no real danger of this in practice since the electrodes are always sufficiently far apart to prevent it from happening. A leakage current in its passage from one electrode to the other is almost bound to go to earth through one or other of the metal parts used in the construction of the sign.

I find it difficult to understand Major Solomon's point about my statement that current is the factor determining the intensity and nature of a shock. My intention was to make it clear that no matter how high or how low the voltage applied to the human body no serious damage would be done if the current through the body did not exceed 15 milliamp. In giving protection against electric shock we have to assume the worst possible conditions when the whole of the leakage current passes through the body, and therefore the device must always operate when the total leakage current amounts to 15 milliamp. or more.

In conclusion, I should like to express my thanks to Captain Higgins and his staff for arranging the demonstration of the spark-gap protective device operating on open-circuit.

Prof. J. C. Prescott (*in reply*): I think that it will dispel a certain amount of misunderstanding if I say first of all that the analyser was built for a special purpose, namely the analysis of comparatively low-frequency waves, and that the components used in its construction were those immediately available in the laboratory where it was developed. It was described in the paper in the belief that such a piece of apparatus might, under similar circumstances, be useful again.

I fully appreciate that so far as sensitivity, and the rapidity with which readings can be obtained, are concerned, it is inferior to the more complicated types of analyser which have been mentioned by Dr. Whitehead. The instrument I have described is, as he points out, unsuitable for the measurement of frequencies which are not an integral multiple of some fundamental, and I heartily endorse his remarks about electrometers among young engineers, in which environment their mortality rate is high. The accuracy of the analyser depends in the first degree upon the purity of the analysing wave, and, as Mr. Carter points out, the smaller the synchronizing pulse imposed on this wave the greater will be the accuracy. In developing the instrument, the synchronizing pulse was reduced as far as possible and its magnitude limited to that necessary for holding the oscillator in synchronism with the wave under analysis in the conditions of frequency variation to be met with in motor-driven alternators. With the relative magnitudes of synchronizing pulse and analysing wave cited in the paper, the errors induced by the former at fundamental frequencies up to about 500 cycles per sec. are very small. I am not sure that I agree with Mr. Carter that the oscillating circuit is "detuned" in order to obtain maximum electrometer deflection. It seems to me that the maximum will occur when the harmonic of the wave under analysis is in phase with the analysing wave (which has, of course, the frequency of the harmonic) produced by the oscillator, and that, so far as this harmonic and the analysing wave are concerned, the circuit is definitely in tune. But I do agree that some phase-splitting device would be useful, though I think I would prefer to apply this between the input terminals and the thyratron circuit, since the adjustment of a phase-splitting device across the terminals of the oscillating circuit might cause difficulties by putting this circuit out of tune.

Prof. Marchant raises the question of the purity of the wave obtained from the dynatron oscillator. When developing the analyser I had access to some results obtained by Prof. Marchant and Dr. Houldin, and my own experience with this type of oscillator has confirmed their observations that, for high purity of wave-form, the L/C ratio of the oscillating circuit should be low and that the bias applied to the first grid of the oscillating valve should be as large as possible. The former requirement can be fulfilled by suitable design of the circuit, and the latter by setting the grid bias to the highest negative value at which stable oscillations are maintained.

ELECTRICAL TEMPERATURE MEASUREMENTS IN PHYSIOLOGY

By Professor A. V. HILL, O.B.E., Sc.D., F.R.S.

(Abstract *of Lecture delivered before the* Meter and Instrument Section, *20th May*, 1938.)

Although the resistance thermometer is used either with an indicator or with a recorder for clinical purposes, or in the form of a hot-wire microphone for measuring pulse wave velocities, or as a hot-wire anemometer for measurements on rates of air and blood flow, the fact that energy must be given to the thermometer renders it useless for the determination of the energy liberation associated with nervous and muscular action.

The thermocouple in the form of the radiation thermopile has several applications in physiology, but it is as a delicate contact temperature-measuring device that it is most widely used.

As an example of the diversity of application of delicate thermocouples may be cited their biological use in the measurement of vapour pressure. The osmotic pressure, which is determined by the sum of the molecular and ionic concentrations, is of extreme importance in biology, and in the human body the osmotic pressure of the body fluids is very finely regulated.

A direct measurement of osmotic pressure is impossible, and the use of the boiling or freezing point is inconvenient, since with the first the constitution of the body fluids would be changed and with both the quantity of liquid necessary is excessive.

The method adopted has been to measure osmotic pressure by the determination of the lowering of vapour pressure of watery solutions by means of a differential thermopile. A symmetrical pile is placed in a moist chamber, and on one face of the pile is placed a strip of filter paper dipped in a solution of known vapour pressure. On the other face of the pile is placed an identical strip of filter paper dipped in the unknown solution. Both faces will cool owing to evaporation if their vapour pressures are greater than that of the surrounding vapour. If the vapour pressures differ, the degrees of cooling of the two faces of the thermopile will differ, and the resultant temperature-difference is indicated on a galvanometer.

The sensitivity of the method is such that, using thermocouples comprising two single loops of very fine wire, one loop to each liquid, it has been possible to investigate the osmotic pressure of the body fluids of such small creatures as a fly or a larva. Lately these minute thermocouples have been used for studying the osmotic pressure of the fluids inside the human eye, of which only very small quantities can be obtained.

Physiologists have speculated for many years about the nature of the transmission of messages from place to place in the nervous system. It is known that the velocity of the messages depends on the character of the nerve, and that the passage is associated with an electrical change. It had been thought that the energy was transmitted in some way by wave motion analogous to a sound wave or an electro-magnetic wave, and the failure to measure any heat production supported this view, although the velocity of travel was relatively slow. Recently, by constructing very thin and sensitive thermopiles, it has been possible to measure the heat liberation associated with nervous action. The thermopile is in direct contact with the nerve and must be extremely well insulated electrically. No available galvanometer was sufficiently sensitive to measure the e.m.f. developed, and thermionic amplification was not possible since only a few microvolts were liberated. A photo-electric double galvanometer system was adopted, and by this means an effective thermal sensitivity of 500 metres' deflection per degree Centigrade was obtained. Even this sensitivity is only just adequate, since the immediate rise of temperature in a nerve following a single impulse is only a few hundred millionths of a degree Centigrade, and a good many impulses must pass before the heat deflection is measurable.

Since the process is rapid, a compromise must always be made between sensitivity and speed of response, both of the thermopile and of the galvanometer; thus, if the thermopile is made thin and the number of couples is increased, the resistance rises and the shorter the period of the galvanometer used the less sensitive the system.

These difficulties are not so troublesome in the measurement of the heat liberation associated with muscular action, where a twitch of a single muscle fibre will be associated with a rise in temperature of several thousandths of a degree Centigrade, and a prolonged movement with even more.

The thermocouples now used for muscle experiments comprise soldered elements of constantan and manganin rolled out to a thickness of about 0·015 mm., in which form they are both extremely quick in picking up the temperature of the muscle and slow in conducting heat away along their length. They are insulated electrically by mica and bakelite varnish only 15 μ in thickness.

The galvanometers first used were of the moving-magnet type, but when they were damped satisfactorily it was not possible to reduce the period below 0·5 sec. It proved necessary for muscle experiments to have a period of the order of one-tenth this value, and the method adopted was once again a combination of two short-period moving-coil galvanometers with a photo-electric cell. The thermopile is connected to the primary galvanometer, and the beam of light reflected from this galvanometer falls on a differential photo-electric cell. Part of the current from the photo-electric cell deflects the secondary galvanometer, and part is fed back to the primary galvanometer in an opposite sense to that producing its initial deflection, thus making the restoring couple stronger and, in effect, the period more rapid.

This method has been further developed, and has led to the development of a device whereby electrically the characteristics of a galvanometer system can be varied at will.*

Devices such as these have made it possible to obtain, in response to the electrical heating of a muscle, galvanometer deflections which rise to 85 % of their maximum in 0·05 sec. and to 50 % in a few millisec. Eighteen years ago, when the work was first commenced, the time taken to reach a 50 % deflection was 1·7 sec. and to reach full deflection as much as 3 to 4 sec.

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* O. H. Schmitt: *Journal of Scientific Instruments*, 1938, vol. 15, p. 234.

AN EXPERIMENT ON ELECTROMAGNETIC INDUCTION BY LINEAR MOTION[*]

By PROFESSOR E. G. CULLWICK, M.A., Associate Member.[†]

(*Paper first received* 5*th November*, 1938, *and in revised form* 13*th March*, 1939.)

SUMMARY

An experiment is described which shows that the e.m.f. induced in a circuit consisting of a cylindrical tube moving concentrically along a straight current-carrying conductor, and stationary leads connected to the inner and outer surfaces of the tube by sliding contacts, is independent of the permeability of the tube.

The experiment appears to be of some interest in connection with the question of the correct formulation of the laws of electromagnetic induction.

INTRODUCTION

Consider a cylindrical iron tube, Fig. 1, moving concentrically along a straight conductor carrying a steady current. On the inner and outer surfaces of this tube rest fixed brushes which are connected by stationary wires to a galvanometer or voltmeter. Will the measured e.m.f. be independent of the permeability of the tube. or in other words will the e.m.f. be identical for similar tubes of iron and brass?[‡]

The problem is interesting as an illustration of the correct method of applying two alternative theories of electromagnetic induction:—

(A) The classical Maxwell–Lorentz theory of a fixed aether. For a closed conducting circuit it is well known that the aether (and all magnetic fields) may be taken as being stationary relative to the observer who applies the theory.

(B) The "moving field" theory, in which it is postulated that a magnet or current-circuit (the "primary"), moving with velocity $\mathbf{v}$ relative to a body, induces an electric intensity $\mathcal{E} = \mathbf{B}_0 \times \mathbf{v}$ at a point in the body, where $\mathbf{B}_0$ is the component of the flux-density at the point contributed by the primary. In general, if the body is magnetic, the resultant flux density at a point in it may be expressed by $\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_i$, where $\mathbf{B}_0$ is the component due to external magnets or current-circuits and $\mathbf{B}_i$ is the component contributed by the magnetic atoms in the body. $\mathbf{B}_0$ is to be taken as sharing the motion of its source (or if due to various sources moving with different velocities the components of $\mathbf{B}_0$ share the velocities of the sources of these components), while $\mathbf{B}_i$ is to be taken as sharing the motion of the magnetic body. In this theory all magnetic fields are regarded as being due to electric currents (moving charges), and free magnetic poles are not considered to exist. $\mathbf{B}_i$ is a function of $\mathbf{B}_0$, together with the shape and magnetic properties of the body, and except in certain simple cases is difficult to calculate.

Further, if the magnetomotive force of the primary is changing, resulting in a changing magnetic field *relative to the primary*, a "transformer" e.m.f. is also induced which for a closed secondary circuit is given by

$$e = -N\frac{\partial\phi}{\partial t}$$

the induced electric field at a point in the secondary being

$$\mathcal{E} = -\frac{\partial \mathbf{A}}{\partial t}$$

where $\mathbf{A}$ is the vector potential at the point, both e and $\mathcal{E}$ being calculated by considering the primary circuit to be momentarily at rest relative to the secondary.

This theory differentiates clearly between "motional" and "transformer" induction, the former being caused by relative motion between a conductor and magnets or current-circuits, while the latter is due to changing currents. The Maxwell–Lorentz theory, as the present problem shows, does not make a similar distinction.

According to the Maxwell–Lorentz theory, in order to calculate the e.m.f. induced in the closed circuit of Fig. 1 we must consider two effects:—

(1) The motion of the iron tube through the total or resultant magnetic field, B, in its interior. This will result in a motional component of e.m.f. proportional to Bv, or $B_0\mu v$, where B_0 is the magnetic field when $\mu = 1$, μ is the permeability of the iron, and v is the velocity of the tube.

(2) The rise of the magnetic field in the space through which the top of the tube travels, in a short time δt, as it moves into the voltmeter circuit will induce an e.m.f. in the closed circuit equal to the rate at which the flux. in this space increases. That is, it will result in a "transformer" component of e.m.f. proportional to $B\left(1 - \frac{1}{\mu}\right)v$ in a direction opposite to the first component of e.m.f.

The e.m.f. measured will therefore be proportional to B_0v, and will be independent of the permeability of the moving tube.

By the moving-field theory, however, the tube is to be taken as moving through B_0, the stationary field of the stationary axial wire, only, and the field $B_i = (\mu - 1)B_0$ of the iron atoms is to be taken as moving with the tube. On account of the symmetry the field B_i is confined to the interior of the tube, and hence cannot induce any e.m.f. in the stationary leads. Further, since no currents are changing in the primary circuit, there is no "transformer" component of e.m.f. Hence the measured e.m.f. is seen immediately to be proportional to $B_0 v$.

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal*, without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

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[‡] The problem was suggested as a fundamental experiment by A. H. FINLAY (*Journal I.E.E.*, 1936, vol. 79, p. 344) in the discussion of the paper "Some Investigations on the Axial Spin of a Magnet," by W. CRAMP and E. H. NORGROVE (*ibid.*, 1936, vol. 78, p. 481).

Now let an observer who travels with the tube calculate the e.m.f. by each theory in turn. If he uses the Maxwell–Lorentz theory, then he takes the magnetic field of the conductor as stationary relative to himself, and he finds the e.m.f. to be due to the motion of brushes, leads, and voltmeter, through this field. In other words, the physical phenomena, though leading to the same result, appear totally different to the two observers.

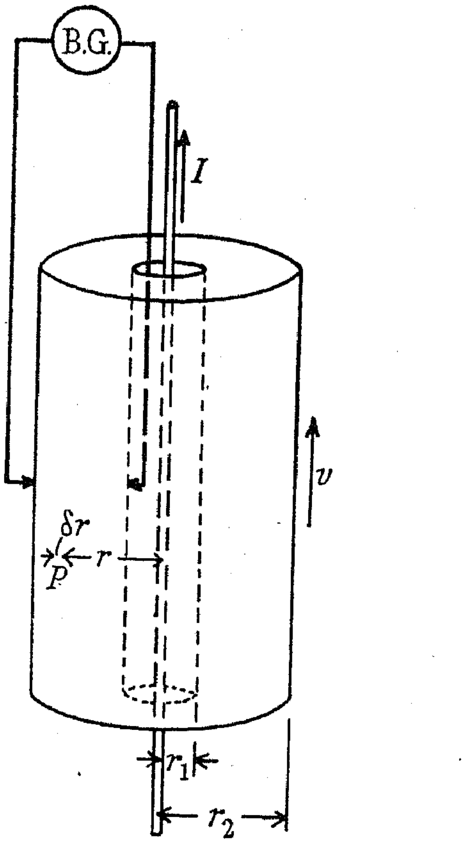

Fig. 1

On the other hand, if the moving observer applies the moving-field theory, he accepts the motion of the field B_0 relative to himself, and finds the e.m.f. to be induced in the tube by this moving field. Thus the moving-field theory, as applied by different observers, gives a definite and unambiguous answer as to the "seat" of the induced e.m.f.; the Maxwell–Lorentz theory, however, is ambiguous, for the seat of the e.m.f. depends upon the motion of the particular observer who applies the theory.

It therefore appears that the moving-field theory is more in keeping with the principle of the restricted theory of relativity than the Maxwell–Lorentz theory.

Although both the moving-field and Maxwell–Lorentz theories, properly applied, are thus seen to lead to the same result, it appeared that, owing to the existence of a certain amount of confusion and disagreement about the correct statement of the laws of electromagnetic induction, a direct appeal to experiment might be of some interest.

METHOD OF MEASUREMENT

If I is the steady current in the axial wire, v the velocity of the tube, r_1 and r_2 the inner and outer radii of the tube, the e.m.f. in the voltmeter circuit is, by either theory,

$$E = 2Iv \log_e \frac{r_2}{r_1} \text{ (absolute c.g.s.)} \quad . \quad . \quad . \quad (1)$$

Let R be the total resistance of the completed circuit, and l the length of travel of the cylinder while in contact with the brushes. Then, if we neglect the inductance of the circuit (i.e. if we assume that the current reaches its steady value, in the closed circuit, in an indefinitely short interval of time), the quantity of electricity passing through the circuit in the time δt, during which the circuit is closed, will be

$$Q = \frac{E}{R} \cdot \delta t$$

But $v = l/\delta t$, so that

$$Q = \frac{2Il}{R} \log_e \frac{r_2}{r_1} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

which is independent of the velocity, v, of the cylinder. If the time δt is appropriately short, a ballistic galvanometer can be used to measure Q.

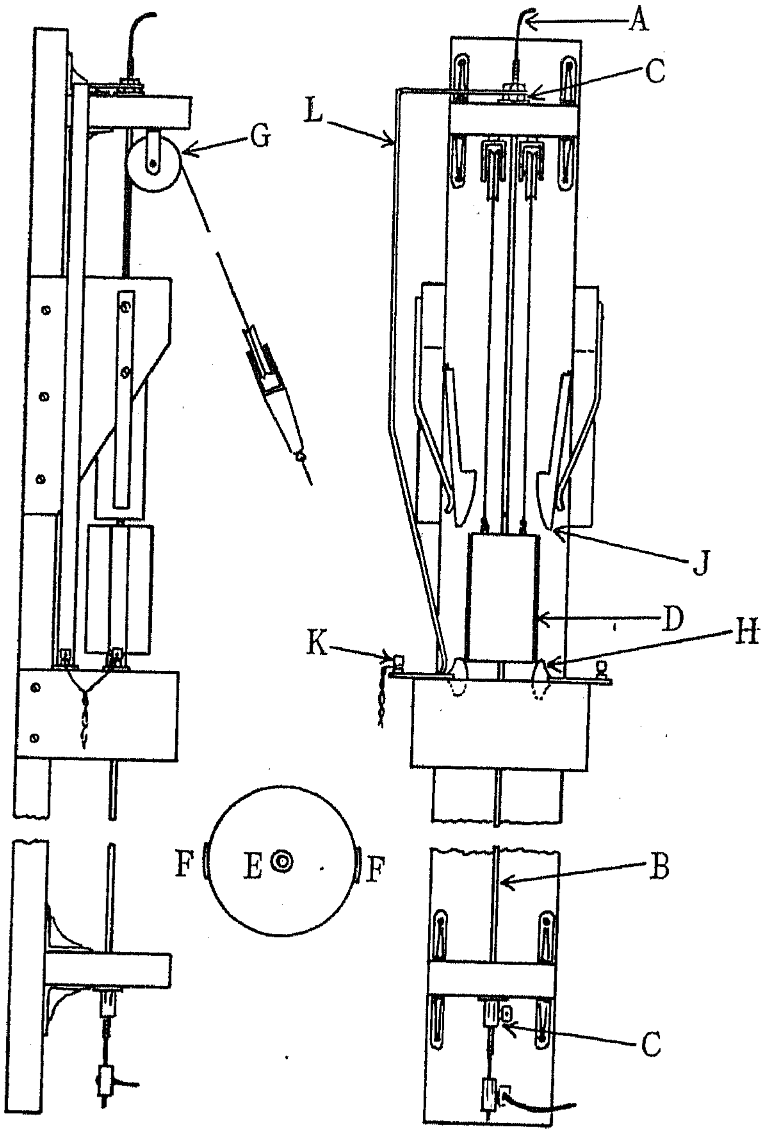

Fig. 2

DESCRIPTION OF THE APPARATUS

A straight insulated copper wire (A, Fig. 2) was located inside a vertical brass tube B of $\frac{1}{4}$ in. outside diameter.

Two cylinders, D, were constructed, one of cast brass and one of mild steel, each with an axial hole of diameter sufficient to allow the cylinder to slide freely along the tube, at the same time maintaining electrical contact. In order to prevent thermal e.m.f.'s due to frictional heating of the iron-brass contacts, the iron cylinder was fitted with a brass bushing, E, $\frac{3}{8}$ in. external diameter, and strips of sheet brass, F, 1 in. wide were soldered on the outside of both cylinders, thus maintaining the outer dimensions of the two cylinders, and hence the value of l, as similar as possible.

The outer diameter of each cylinder was 3·343 in. without the strips, the diametrical distance between the outer surfaces of the strips F being 3·393 in. for the iron cylinder, and 3·397 in. for the brass cylinder. The diameter of the axial hole was 0·254 in. for the iron, and 0·260 in. for the brass cylinder. Each cylinder was 6·62 in. long.

During its travel, the cylinder made contact with two spring-brass brushes, H, arranged diametrically opposite each other and electrically connected, while the brass tube provided the sliding contact with the inner surface of the cylinder. A retaining device J was arranged to hold the cylinder when it had reached the top of its travel.

The ballistic galvanometer was connected to the terminals K by means of twisted lamp-cord. One of these terminals was connected to the brushes H, while the other, by means of a heavy brass strip L, was connected to the upper end of the brass tube.

APPROXIMATE CALCULATED VALUE OF THE EFFECT

For the iron cylinder r_2/r_1 was 13·36 so that, for a velocity of about 0·6 metre per sec. the induced e.m.f. should be about $3\cdot11 \times 10^{-7}I$, where I is the current (amperes) in the axial wire. The highest value of I used was 90 A, giving about 28 μV.

The length of travel of the cylinder while in contact with the brushes was 19·5 cm. The resistance of the circuit, R, was 51·3 ohms, so that, from (2),

$$Q = 1\cdot970 \times 10^{-9}I \text{ coulomb}$$

If $I = 90$, $Q = 0\cdot1773$ micro-coulomb.

The galvanometer sensitivity was 0·011 micro-coulomb per mm. at 1 m. scale distance; the scale was 1·89 m. from the mirror, so that a current of 90 amp. should produce an undamped swing of 3·05 cm. The damping factor was found to be 1·04, so that the first swing should be 2·93 cm.

This calculation is based on the assumption that the current in the galvanometer circuit rises instantaneously to its steady value as soon as contact is made. Owing to the inductance of the circuit this is not strictly true, and as the current falls suddenly when contact is broken the experimental readings would be expected to be smaller than the calculated value. Since the purpose of the experiment was comparison only, it was not thought necessary to calculate this effect.

The time of contact was of the order of 0·25 sec., and as the period of the galvanometer was 25 sec. no appreciable error arose from assuming the swing to be truly ballistic.

EXPERIMENTAL RESULTS

Final readings were taken after eliminating some troublesome thermo-electric e.m.f.'s. It was found from preliminary tests that consistent results could be obtained by operating the cylinder by hand, readings being taken for both up and down movements. Under conditions of equal temperature everywhere, runs taken with no current in the axial wire gave zero deflection for each cylinder, thus confirming Hering's experiment,* but after the current had heated the brass tube deflections were obtained under zero-current conditions. To prevent variation of this effect a regular procedure of taking the runs was adopted. The deflections for such thermal e.m.f.'s were always on the red side of the scale.

No difference between "cylinder up" and "cylinder down" readings could be detected, the readings for a given value and direction of current being equally divided between up and down movements, though of course these readings occurred on different sides of the scale zero. Approximately equal numbers of readings were taken for each direction of current in the axial wire.

The following were the final results, the brass cylinder readings being corrected to allow for the small differences in the inner and outer radii of the two cylinders.

Iron cylinder	*Brass cylinder*
$I = 90$	
Reds: 2·973 ± 0·145 (30)	Reds: 2·957 ± 0·093 (27)
Blacks: 2·538 ± 0·190 (30)	Blacks: 2·476 ± 0·117 (25)
	Mean: 2·717 ± 0·076
Mean: 2·755 ± 0·120	*Corrected mean:* 2·740 ± 0·076
$I = 60$	
Reds: 1·941 ± 0·122 (29)	Reds: 2·012 ± 0·077 (13)
Blacks: 1·673 ± 0·102 (31)	Blacks: 1·603 ± 0·092 (15)
	Mean: 1·807 ± 0·060
Mean: 1·807 ± 0·079	*Corrected mean:* 1·822 ± 0·060

(The numbers in brackets after the readings denote the number of good readings in each case. The number of rejected readings varied from 0 to 5.)

COMMENTS

Compared with the readings for the brass cylinder, the iron-cylinder readings are 0·55 % high for 90 amp., and 0·82 % low for 60 amp. The ratios of the 90-amp. mean readings to the 60-amp. mean readings were:

Iron: 1·525 (1·7 % error) *Brass:* 1·504 (0·27 % error)

The readings are from 6 to 6½ % lower than the theoretical value, and this is probably caused chiefly by the effect of the inductance of the circuit, and partly by slight errors in the measured values of I, l, and R.

Although the above results are conclusive, the experiment does not provide a means of proving either the Maxwell–Lorentz theory or the moving-field theory to be incorrect. Its value lies in settling any possible difference of opinion as to the result, in showing the superior simplicity of the moving-field theory, and in demonstrating the correct method of applying the two theories.

---

* C. Hering: *Transactions of the American I.E.E.*, 1908, vol. 27, p. 1341; and *Electrician*, 1915, vol. 75, p. 599.

Application of the flux-linking or flux-cutting laws alone will, in the fixed-field theory, yield an incorrect result, and both laws must be used and the effects combined. Further, in using the moving-field theory, the various components of the magnetic field must be distinguished: only those components due to moving circuits or magnets should be taken as moving.

An interesting point is that when the arrangement is used to illustrate *motor* action, the galvanometer being replaced by a battery to send current round the circuit, the mechanical force on the iron cylinder will be proportional to B_0I and *not* to BI. The force acting on the current flowing through the cylinder is indeed proportional to BI, but the reaction is shared by the cylinder and the stationary leads. That acting on the cylinder is proportional to $B_0(\mu - 1)I$, and that acting on the stationary part of the circuit is proportional to B_0I, and this is equal to the resultant force on the cylinder.

The author wishes to thank the University of Alberta for making it financially possible to conduct the experiment, and Mr. W. E. Cornish, M.Sc., Assistant Professor of Electrical Engineering, and Mr. E. Jordan, M.Sc., for assistance in performing the experiment.

INSTITUTION NOTES

COUNCIL FOR THE YEAR 1939–1940

The scrutineers appointed at the Ordinary Meeting held on the 27th April, 1939, have reported to the President that the result of the ballot to fill the vacancies which will occur on the Council on the 30th September next is as follows:—

President: Johnstone Wright.

Vice-President: Colonel A. S. Angwin, D.S.O., M.C.

Hon. Treasurer: W. McClelland, C.B., O.B.E.

Ordinary Members of Council: (Members) E. S. Byng; H. J. Cash; P. Good; Prof. W. J. John, B.Sc.(Eng.); A. L. Lunn; H. W. Swann; (Associate Member) Prof. Willis Jackson, D.Sc., D.Phil.; (Associate) D. Z. de Ferranti.

The Council for the year 1939–1940 will therefore be constituted as follows:—

President.

Johnstone Wright.

The Past-Presidents.

Vice-Presidents.

Colonel A. S. Angwin, D.S.O., M.C.
Sir Noel Ashbridge, B.Sc. (Eng.).
J. R. Beard, M.Sc.
Prof. C. L. Fortescue, O.B.E., M.A.

Honorary Treasurer.

W. McClelland, C.B., O.B.E.

Ordinary Members of Council.

T. E. Allibone, D.Sc., Ph.D.
Dr. L. G. Brazier, B.Sc.
E. S. Byng.
H. J. Cash.
P. Dunsheath, O.B.E., M.A., D.Sc.
D. Z. de Ferranti.
P. Good.
Prof. Willis Jackson, D.Sc., D.Phil.
Prof. W. J. John, B.Sc. (Eng.).
Prof. R. O. Kapp, B.Sc.
E. Leete.
A. L. Lunn.
P. L. Rivière.
C. Rodgers, O.B.E., B.Sc., B.Eng.
H. W. Swann.
C. D. Taite.
G. A. Whipple, M.A.
A. P. Young, O.B.E.

Together with the Chairman of the Meter and Instrument Section, the Chairman of the Transmission Section, the Chairman of the Wireless Section, and the Chairman and immediate Past-Chairman of each Local Centre.

PREMIUMS

In addition to the Premiums mentioned on pages 768 and 769 of the June issue of the *Journal* (vol. 84), the Council have awarded the following Premiums for papers read before the Students' Sections during the Session 1938–1939:—

Premiums of the value of £10 each:

Author	*Title of Paper*	*Where read*
R. A. Duncan, B.Sc.	"A Constant-Current System of Ship Propulsion using the 3-Field Generator"	Birmingham
M. E. Rustin	"Electric Discharge Lamps and their Applications"	Manchester

Premiums of the value of £5 each:

Author	*Title of Paper*	*Where read*
F. B. Atkinson, B.Eng.	"Electric Clocks"	Liverpool
F. H. Birch and J. B. Ritchie	"The Testing of Protective Gear on Site"	London
R. Bruce, M.Sc.	"Insulating Materials: Some Types, Properties, and Uses"	Newcastle
G. V. Davy, B.Sc.(Eng.)	"Diesel-Engine Traction"	Leeds
F. A. Drake	"The Design and Layout of Power Station Auxiliaries"	London
R. D. Haigh, M.Eng.	"The Timing of Trunk and Toll Telephone Calls"	Liverpool
D. J. Mynall, B.Sc.	"The Control of Electron Beams"	Birmingham and Rugby

Author	*Title of Paper*	*Where read*
G. F. Swann	"The Principles of Radio Interference Suppression"	Leeds
J. L. Taylor	"Automatic Voltage Regulators for Generators"	Birmingham
J. E. Woollaston	"Automatic Control"	Birmingham and Stafford

MEMBERS FROM OVERSEAS

The Secretary will be obliged if members coming home from overseas will inform him of their addresses in this country, even if they do not desire a change of address recorded in the Institution register.

The object of this request is to enable the Secretary to advise such members of the various meetings, etc., of The Institution and its Local Centres, and, when occasion arises, to put them into touch with other members.

COMMUNICATIONS FROM OVERSEAS MEMBERS

Overseas members are especially invited to submit, for publication in the *Journal*, written communications on papers read before The Institution or published in the *Journal* without being read. The contributor's country of residence will be indicated in the *Journal*. In this connection a number of advance copies of all papers read before The Institution are sent to each Local Hon. Secretary abroad to enable him to supply copies to members likely to be in a position to submit communications.

GRADUATESHIP EXAMINATION RESULTS: MAY, 1939

Passed*

Barber, Alan.
Barker, Stuart.
Baskerville, James Joseph Patrick.
Batcock, Bernard John.
Belsey, Frederick Harold.
Bentley, Donovan Vernon Craigie.
Birrell, Robert Cuthbertson.
Bond, George Dennis.
Brodrick, Alfred Gerald.
Burrows, Arthur Thomas.
Capes, John Philip.
Chambers, George Stanley Martin.
Clark, Reginald.
Coles, Douglas Harry.
Cornish, Reginald Edward.
da Costa, Francis Edward.
Dolman, Frank Kenneth.
Dunsford, Kenneth Martin.
Durston, David Stanley.
Eales, Edward Reginald.
Earl, John Wakelin.
Fergusson, Leonard.
Foster, Fred William.
Frazer, Thomas Athol.
Hales, Ronald Leslie.
Heath, Frederick Walter.
Hickling, Charles Geoffrey.
Hitchin, Herbert.
Hobbs, Edwin Daniel.
Jones, Leslie Gordon.
Jones, Leslie Llewellyn.
Jones, Maurice Clement.
Jones, Patrick Ludlow Fleming.
Jones, Peter Bailey.
Knowles, John.
Levin, Arthur.
Loraine, Thomas Edward.
McOwen, Rowland William.
Mills, Eastall.
Moore, Stephen.

Passed—continued.

Odell, Trevor George.
Palfrey, Harold Charles.
Pilborough, Leslie.
Rix, Edward Alfred.
Rogers, Francis Emil.
Shaw, Arthur Francis.
Shipstone, Bernard Arthur.
Sigee, Eric.
Smith, James Newton.
Sneath, Wilfrid Samue Garwood.
Wash, Geoffrey Henry.
Wharton, William.
White, William Edward.
Whitfield, Harold Raymond.

Passed Part I only

Bowen, Dennis Dawes.
Crampton, Raymond Willows.
Crockart, Andrew.
Dixon, George Wilfred.
Groome, Reginald Gordon.
Kenney, Douglas John.
Kirby, Francis Hamilton.
Long, George Richard.
Mills, Victor Ronald.
Montgomery, Philip Albert.
Palmer, William Clifford.
Read, William Macartney.
Street, Walter George.
Wilson, Arthur Henry.

Passed Part II only

Amorn, Jamun.
Colvin, John Christopher.
Hepworth, Arthur.
Martin, Kenneth Spencer.
Newey, Gordon William Joseph.
Page, Robert Edward.
Patel, Chinubhai Manibhai.
Richardson, George Osborne.
Sheard, John Raymond.
Sykes, William Harrison.

PROCEEDINGS OF THE WIRELESS SECTION

149th Meeting of the Wireless Section, 1st February, 1939

Mr. A. J. Gill, B.Sc.(Eng.), Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 4th January, 1939, were taken as read and were confirmed and signed.

A paper by Messrs. P. R. Coursey, B.Sc.(Eng.), Member, and S. N. Ray, M.Sc., B.Sc.(Eng.), Associate Member, entitled "Electrolytic Condensers" (see page 107), was read and discussed. The paper was illustrated by a cinematograph film and demonstration of apparatus.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

16th Informal Meeting of the Wireless Section, 14th March, 1939

Mr. R. T. B. Wynn, M.A., took the chair at 6.30 p.m.

The minutes of the Informal Meeting held on the 24th January, 1939, were taken as read and were confirmed and signed.

A discussion, opened by Messrs. E. M. Lee, B.Sc., A. H. Cooper, F. R. W. Strafford, and C. N. Smyth, B.Sc.(Eng.), took place on "Interference Suppression at the Listener's End."

At the conclusion of the discussion a vote of thanks was accorded to the openers for their introductory remarks.

150th Meeting of the Wireless Section, 1st March, 1939

Mr. A. J. Gill, B.Sc.(Eng.), Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 1st February, 1939, were taken as read and were confirmed and signed.

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* This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Dr. R. L. Smith-Rose presented a symposium (see page 203) of the following papers on "Direction-Finding":—

"An Improved Medium-Wave Adcock Direction-Finder," by Messrs. R. H. Barfield, M.Sc.(Eng.), Associate Member, and R. A. Fereday, Ph.D. (see vol. 83, page 676).

"A Short-Wave Adcock Direction-Finder," by Messrs. R. H. Barfield, M.Sc.(Eng.), Associate Member, and W. Ross, M.A. (see vol. 83, page 682).

"Radio Direction-Finding on Wavelengths between 6 and 10 metres (Frequencies 50 to 30 Mc./Sec.)," by Messrs. R. L. Smith-Rose, D.Sc., Ph.D., Member, and H. G. Hopkins, B.Sc., Ph.D. (see vol. 83, page 87).

"The Measurement of the Lateral Deviation of Radio Waves by means of a Spaced-Loop Direction-Finder," by Messrs. R. H. Barfield, M.Sc.(Eng.), Associate Member, and W. Ross, M.A. (see vol. 83, page 98).

"A Sense-Finding Device for Use with Spaced-Aerial Direction-Finders," by Mr. R. A. Fereday, Ph.D. (see vol. 84, page 96).

"The Calibration of Four-Aerial Adcock Direction-Finders," by Mr. W. Ross, M.A. (see vol. 85, page 19).

A discussion (see page 207) on the papers then followed, to which Dr. Smith-Rose replied, and, on the motion of the Chairman, a vote of thanks to him and his co-authors was carried with acclamation.

151st Meeting of the Wireless Section, 5th April, 1939

Mr. A. J. Gill, B.Sc.(Eng.), Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 1st March, 1939, were taken as read and were confirmed and signed.

A paper by Mr. N. F. S. Hecht, Member, entitled "Radio in Aviation: a General Survey, with special reference to the Royal Air Force" (see page 215).

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

152nd Meeting of the Wireless Section, 3rd May, 1939

Mr. A. J. Gill, B.Sc.(Eng.), Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 5th April, 1939, were taken as read and were confirmed and signed.

The Chairman announced that the following members had been nominated to fill the vacancies which would occur on the Committee on the 30th September, 1939:—

Chairman: Mr. E. B. Moullin, M.A.

Vice-Chairman: Dr. R. L. Smith-Rose.

Ordinary Members of Committee: Messrs. W. L. McPherson, B.Sc.(Eng.), J. A. Ratcliffe, M.A., and M. G. Scroggie, B.Sc.

In the event of a ballot for the new Committee being required, Messrs. S. R. Chapman, M.Sc., and F. Jervis Smith were appointed scrutineers.

A paper by Messrs. I. L. Turnbull, M.Sc.(Eng.), and H. A. M. Clark, B.Sc.(Eng.), Associate Member, entitled "Audio-Frequency Equipment at the London Television Station," was read and discussed.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

TRANSFERS

The following transfers were effected by the Council at their Meeting held on the 4th July, 1939:—

Student to Graduate

Ambler, Mark.
Bartle, Maurice James, B.Sc.
Beecham, Ronald Arthur.
Black, Keith Marriott.
Collins, Frederick Henry, B.Sc.Tech.
Coyle, Arthur Douglas, B.Sc.Tech.
de Figueiredo, Bruno Filomeno, B.Sc.(Eng.).
Galaway, George Ronald.
Gallop, Peter Jack.
Grant, Francis Cullen.
Griffiths, Charles.
Harmsworth, John Alfred.
Heilner, Wolfgang, B.Sc. (Eng.).
Holbrook, George William, B.Sc.(Eng.).
Jenkins, Tom Cullis, B.Sc. (Eng.).
Morgan, Piers Anthony, B.Sc.
Nangia, Lachman Narain.
Napper, Charles Geoffrey, B.Sc.(Eng.).
Nield, Frederick Arthur.
Nixon, Cecil Walter, B.Sc. (Eng.).
Oliver, Martin Hugh, B.Sc. (Eng.).
Palmer, Ronald Richard.
Panshikar, Chandrashekhar Vishnu.
Pearce, Kenneth Maxwell.
Pugh, Charles Trevor, B.E.
Reed, Neville Stanley.
Sastri, Dorbala Viswanatha.
Seymour, Trevor.
Simms, James Maude.
Stevens, Philip Frederick.
Thomas, Edward Reginald, B.Sc.(Eng.).
Todd, Donald Elliott, B.Sc.(Eng.).
Todd, Douglas, B.Sc.Tech.
Zavala, Fernando.

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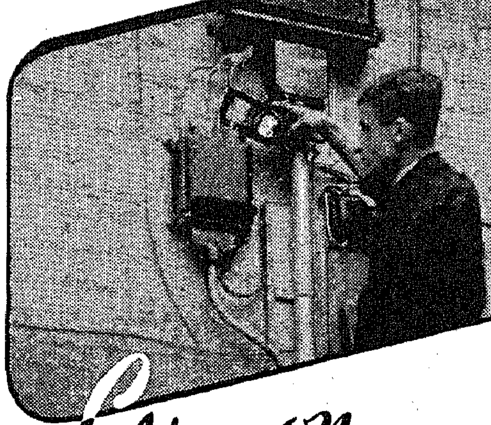

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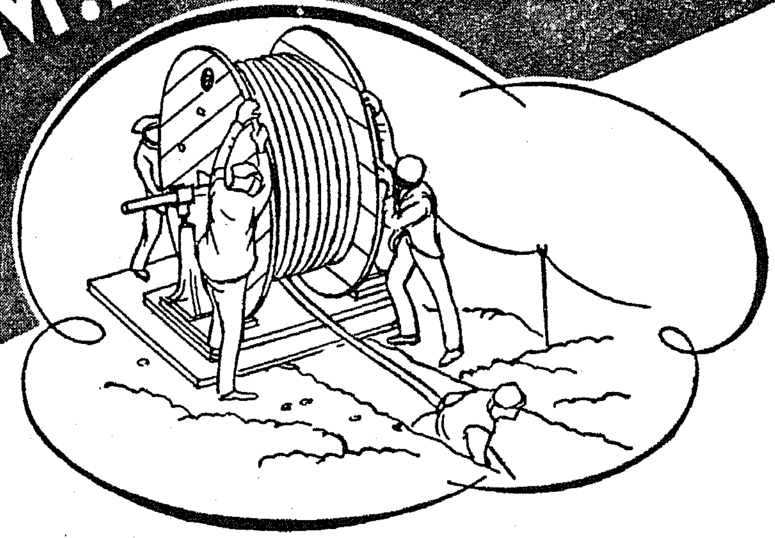

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Johnson & Phillips Ltd.
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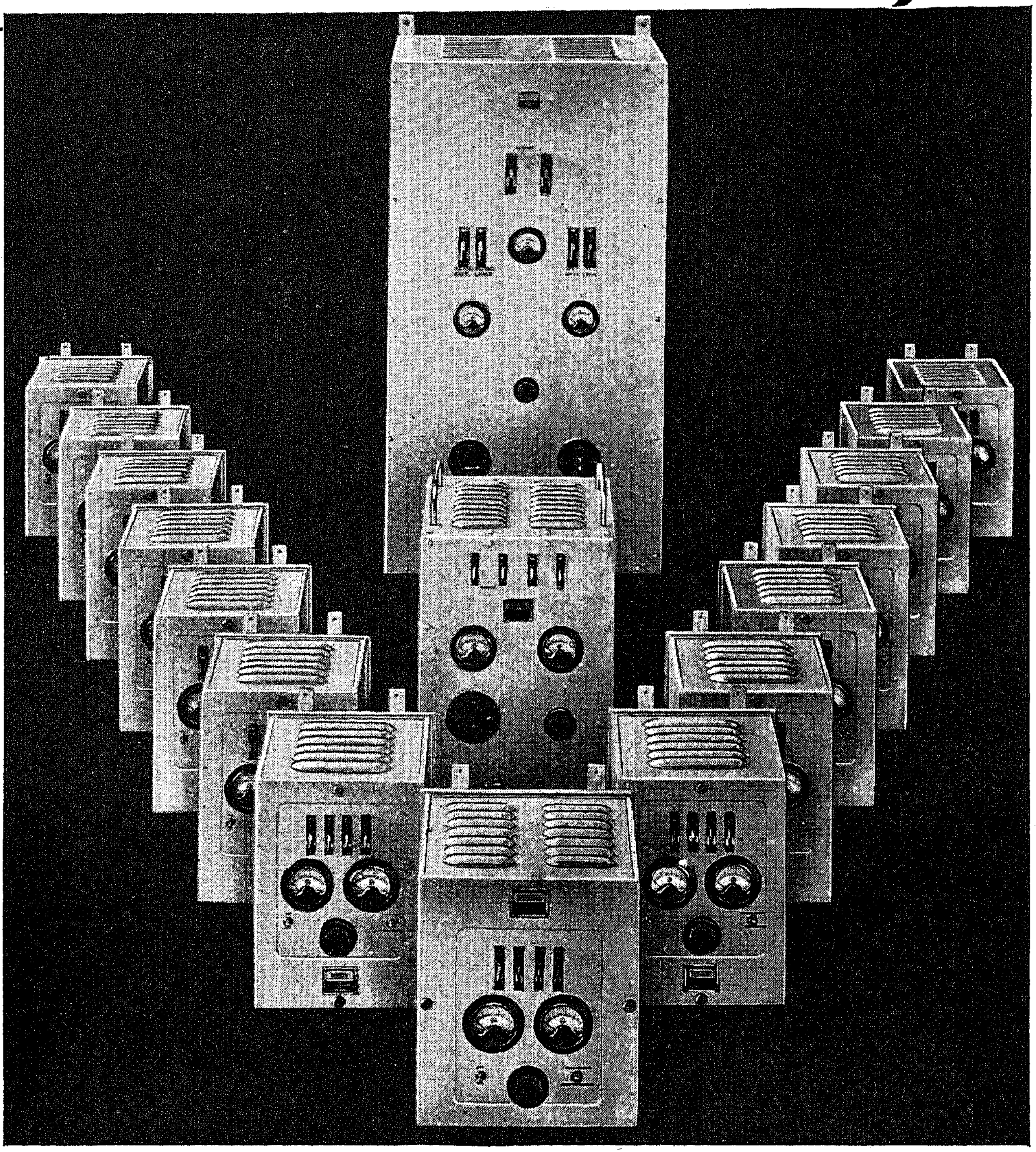

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THE illustration shows a group of battery chargers used in conjunction with S.T.C. Remote Control equipment.

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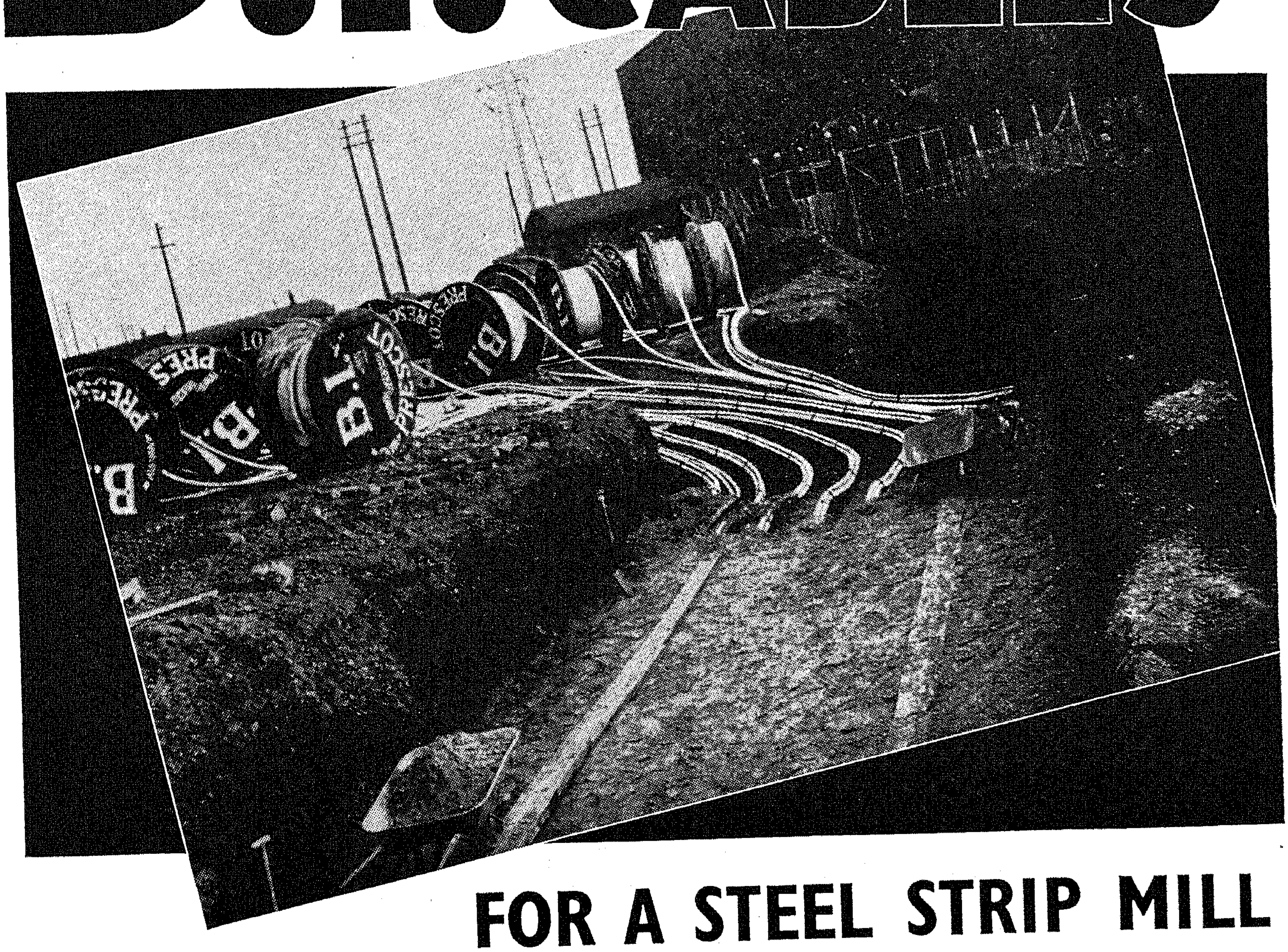

FOR A STEEL STRIP MILL

The illustration shows a duplicate set of 6.6 kV., **B.I. Cables** being laid to feed the new strip mill at the Shotton Iron Works of Messrs. John Summers & Sons, Ltd. The large amount of power required necessitated very heavy conductors and the photograph shows twenty-four 1 sq. in. **B.I. Cables** laid in a trench 16 feet wide by 7 feet deep.

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In the top view note the tubular cross bracing carrying trolley-bus over-head wires. In the bottom view the braced pole in the foreground stands at a six-way junction, where, we are told, it carries the heaviest suspended gear in the country, the total weight being some 3½ tons.

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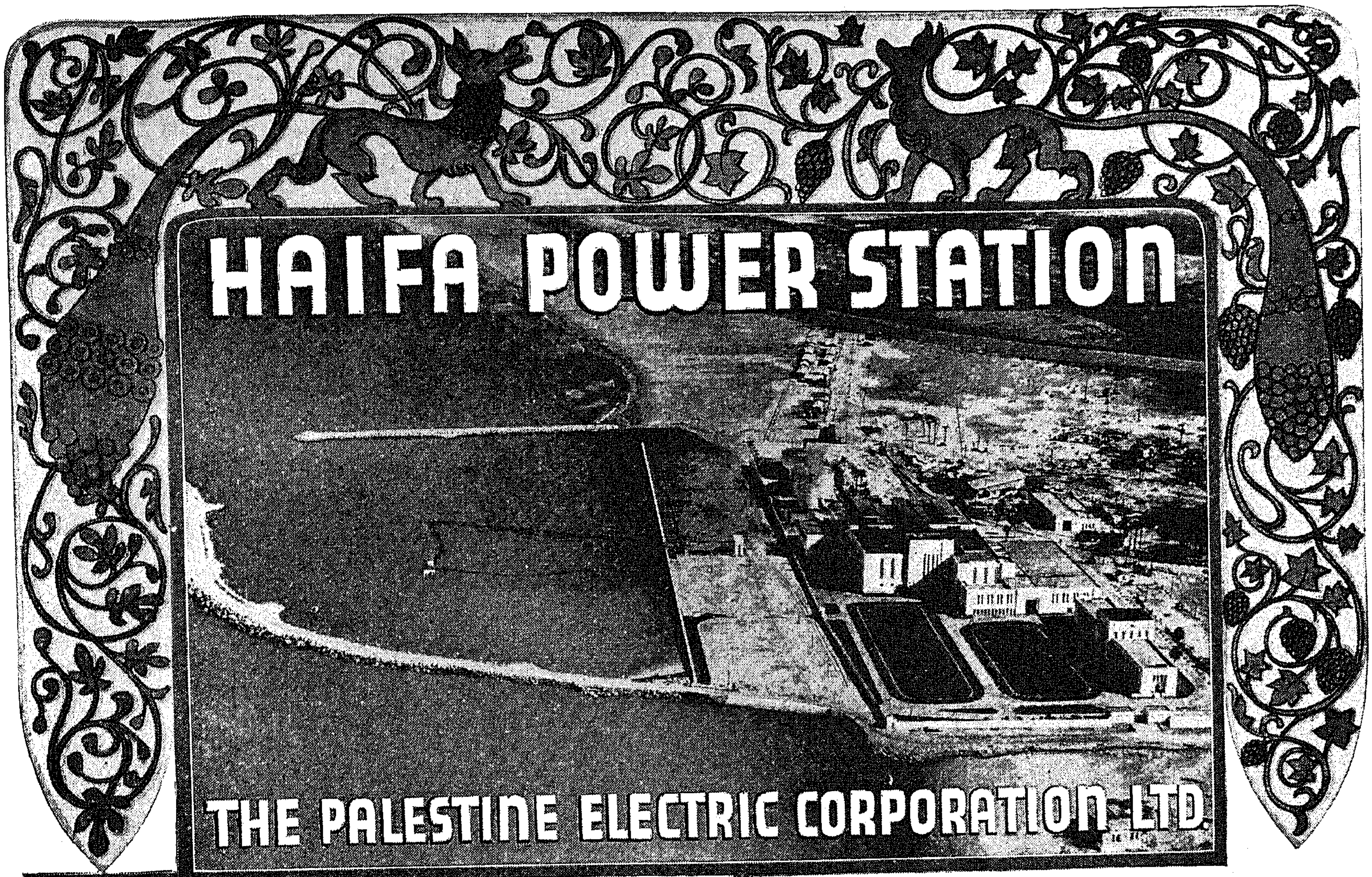
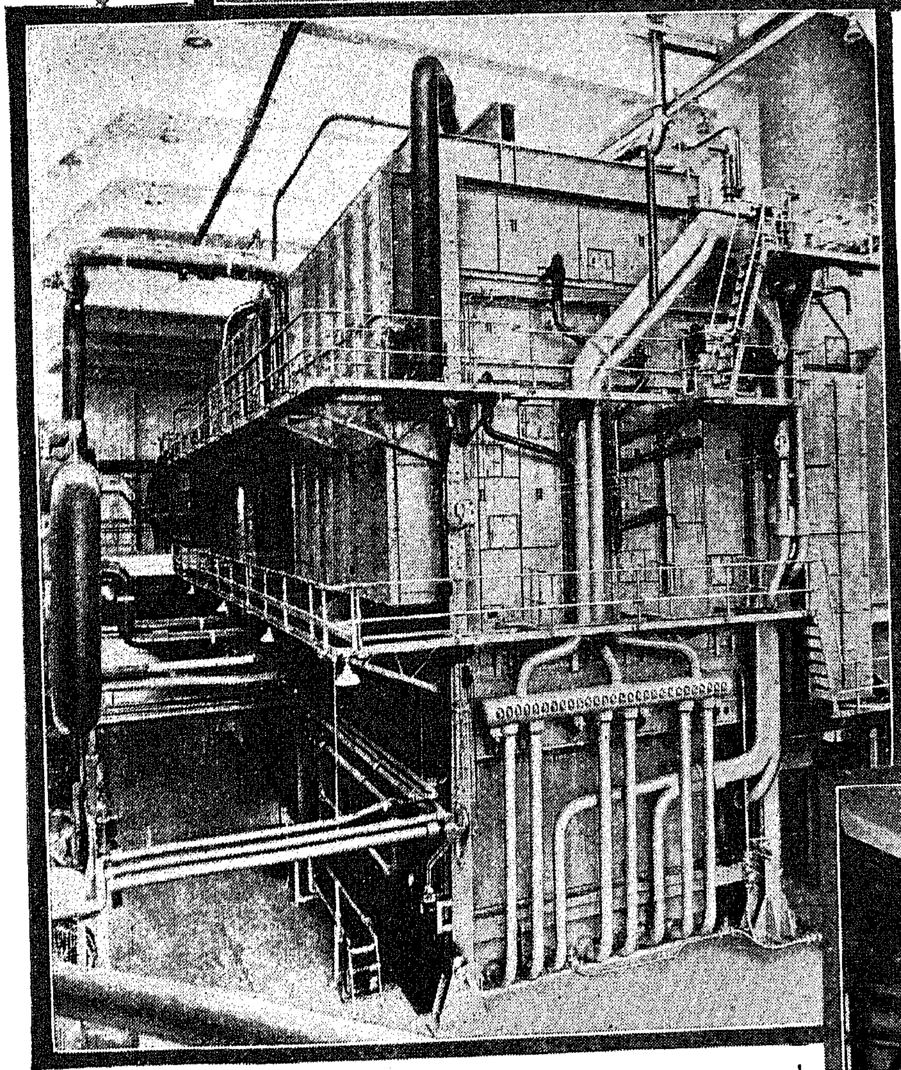




TWO B. & W. Boilers, Nos. 4 & 5, have recently been put into commission at the above Station. These are each of 11,850 sq. ft. h. s., with superheaters for 842°F. 385 lb./sq. in., and a normal evaporation of 105,600 lb./hr.

Each boiler is equipped with a BAILEY furnace and is fired by the latest design of B. & W. Oil Firing Equipment.

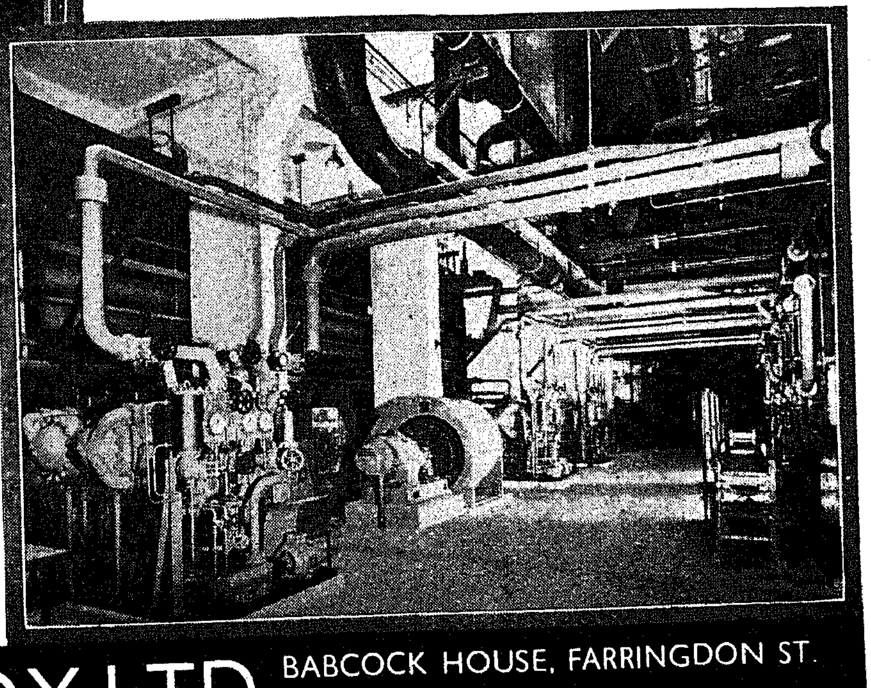
The Contract also includes Economisers, Steel Stayed Chimneys, Soot Blowers, Feed Water Treatment Plant, Fans, etc.

The illustrations show :

Top : An aerial view of the Power Station.

Centre : A view of the Boilers.

Bottom : Pumping and Heating Units, Fans, and Firing Aisle.



Two similar B. & W. boilers, each with a normal evaporation of 70,400 lb./hr. at 842°F. and 385 lb./sq. in., have also been installed in the Reading Power Station of The Palestine Electric Corporation Ltd.

All boilers referred to in this advertisement have Babcock Class One Fusion Welded Drums.

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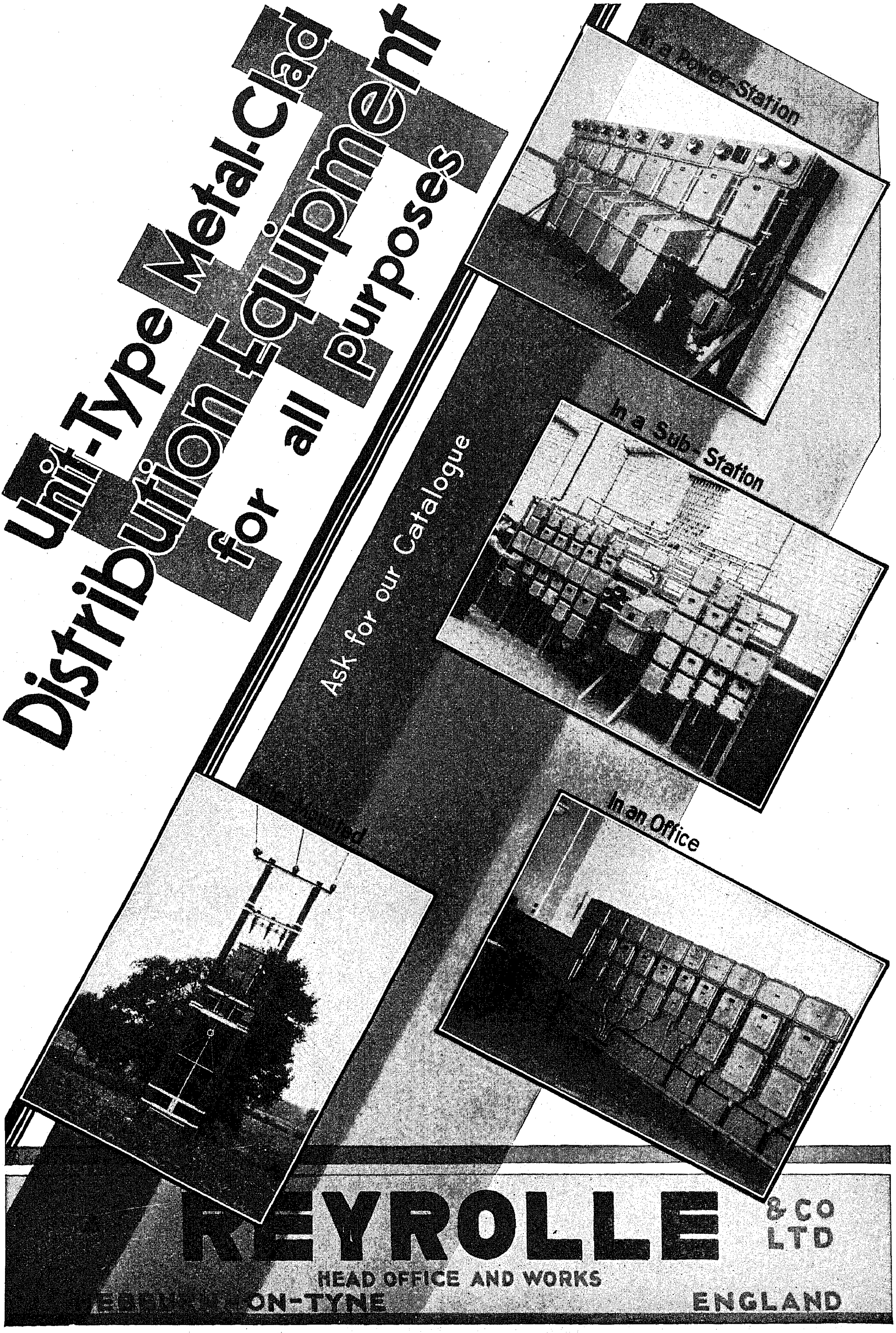

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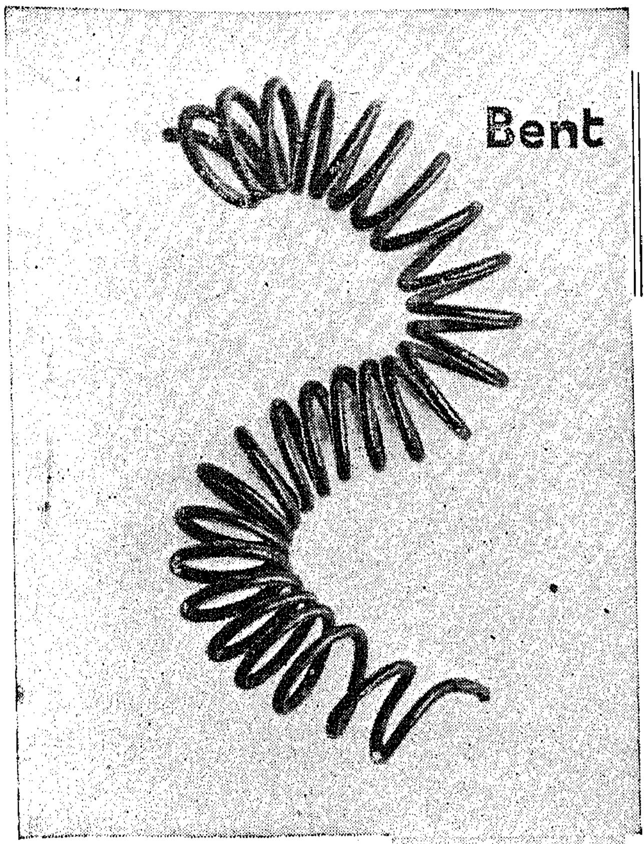

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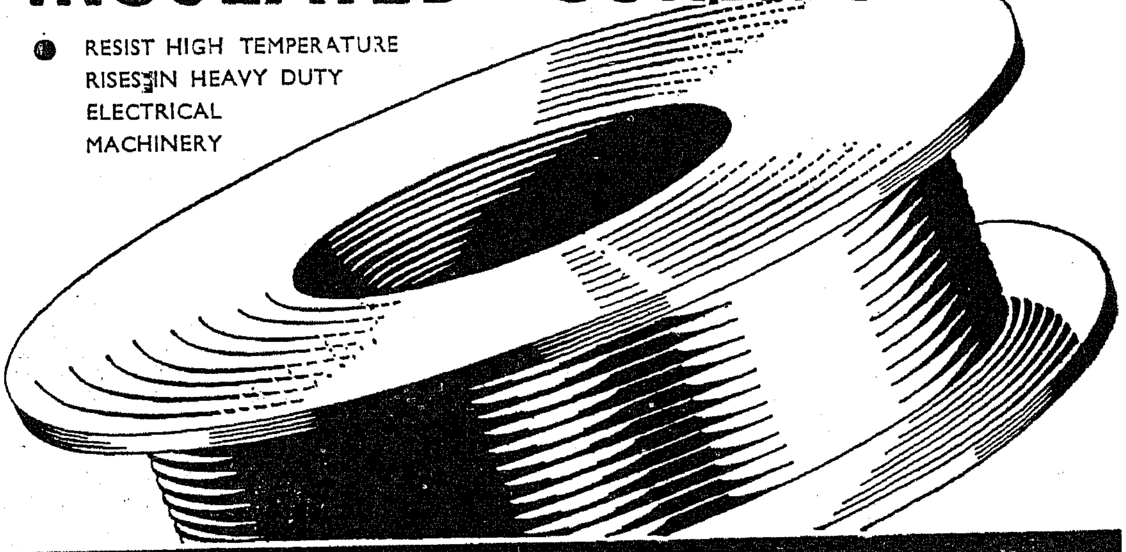

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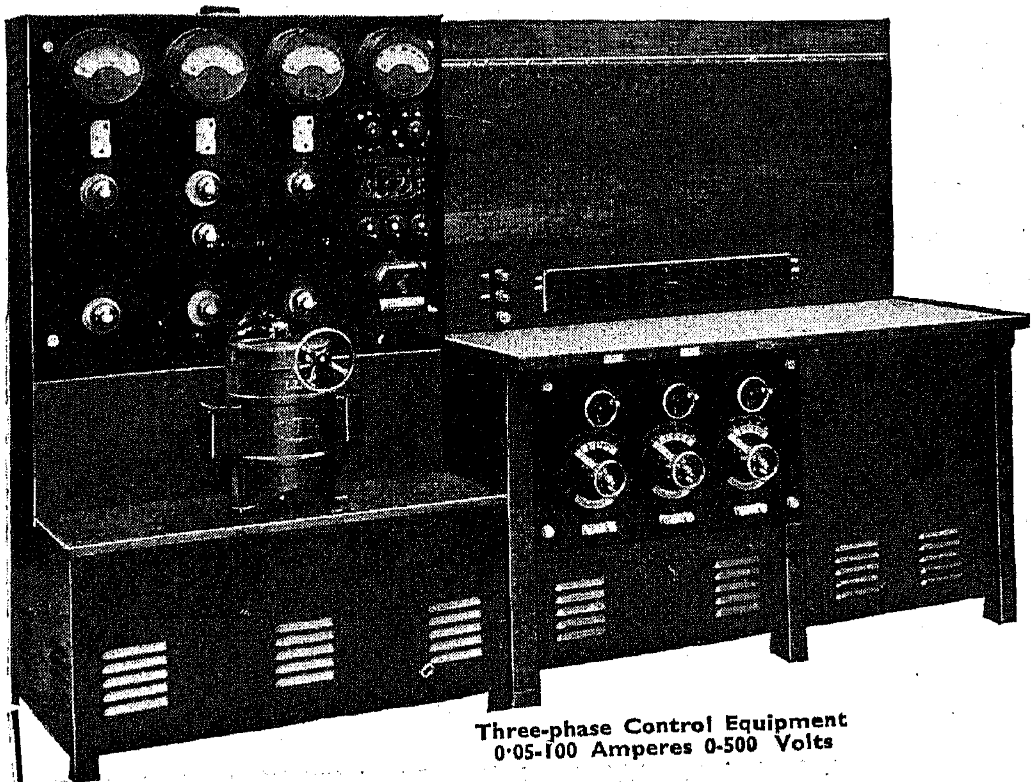

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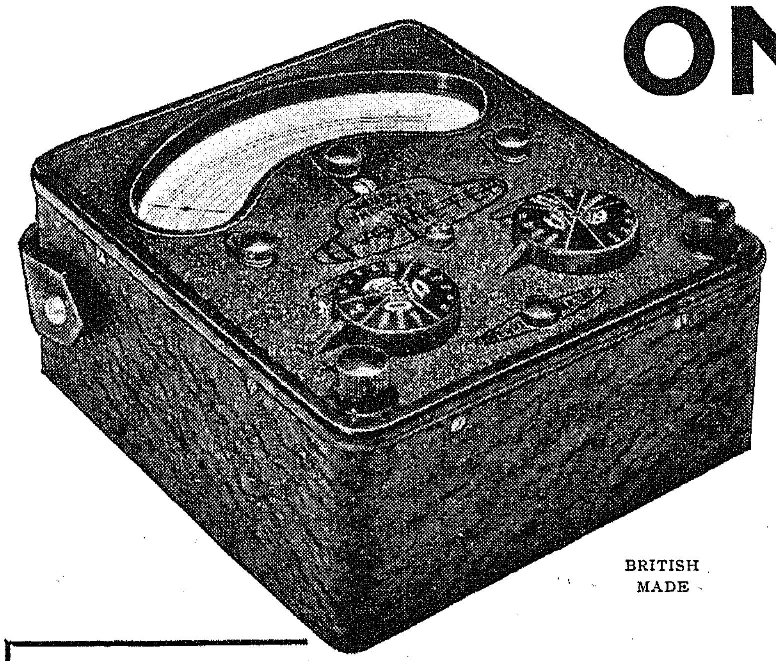

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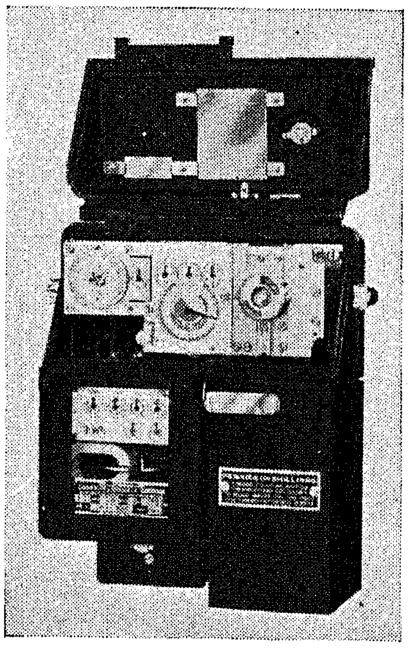

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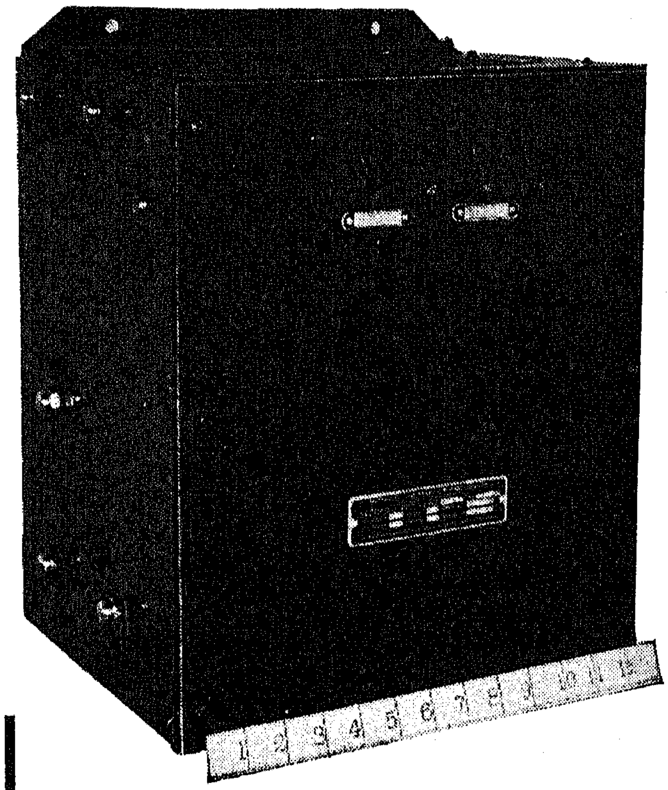

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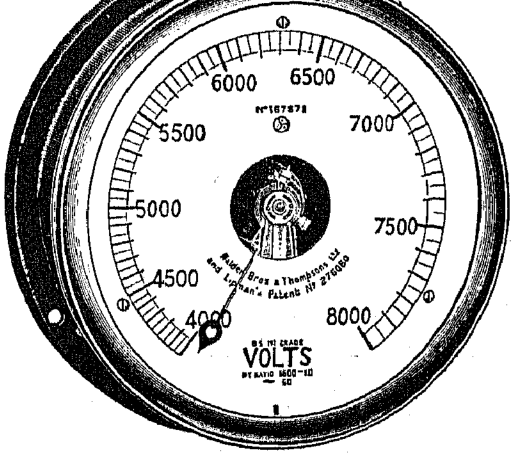

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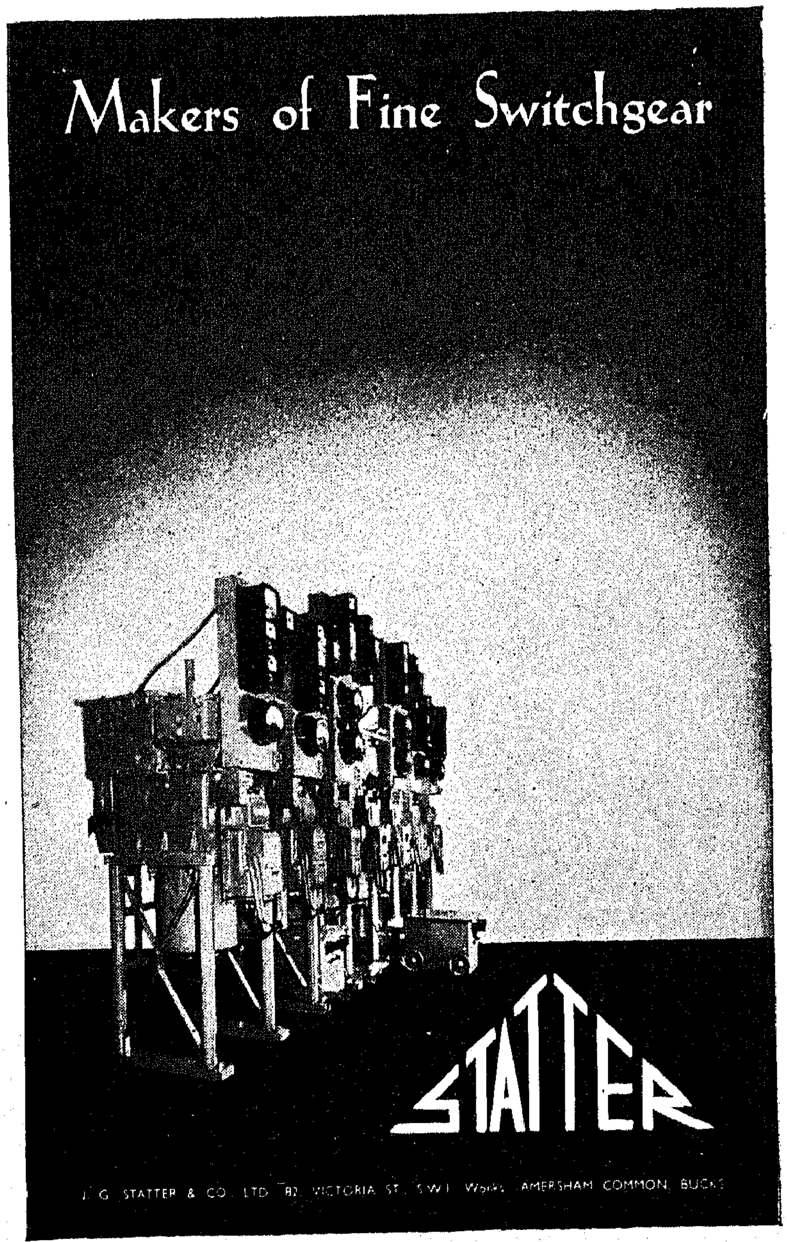

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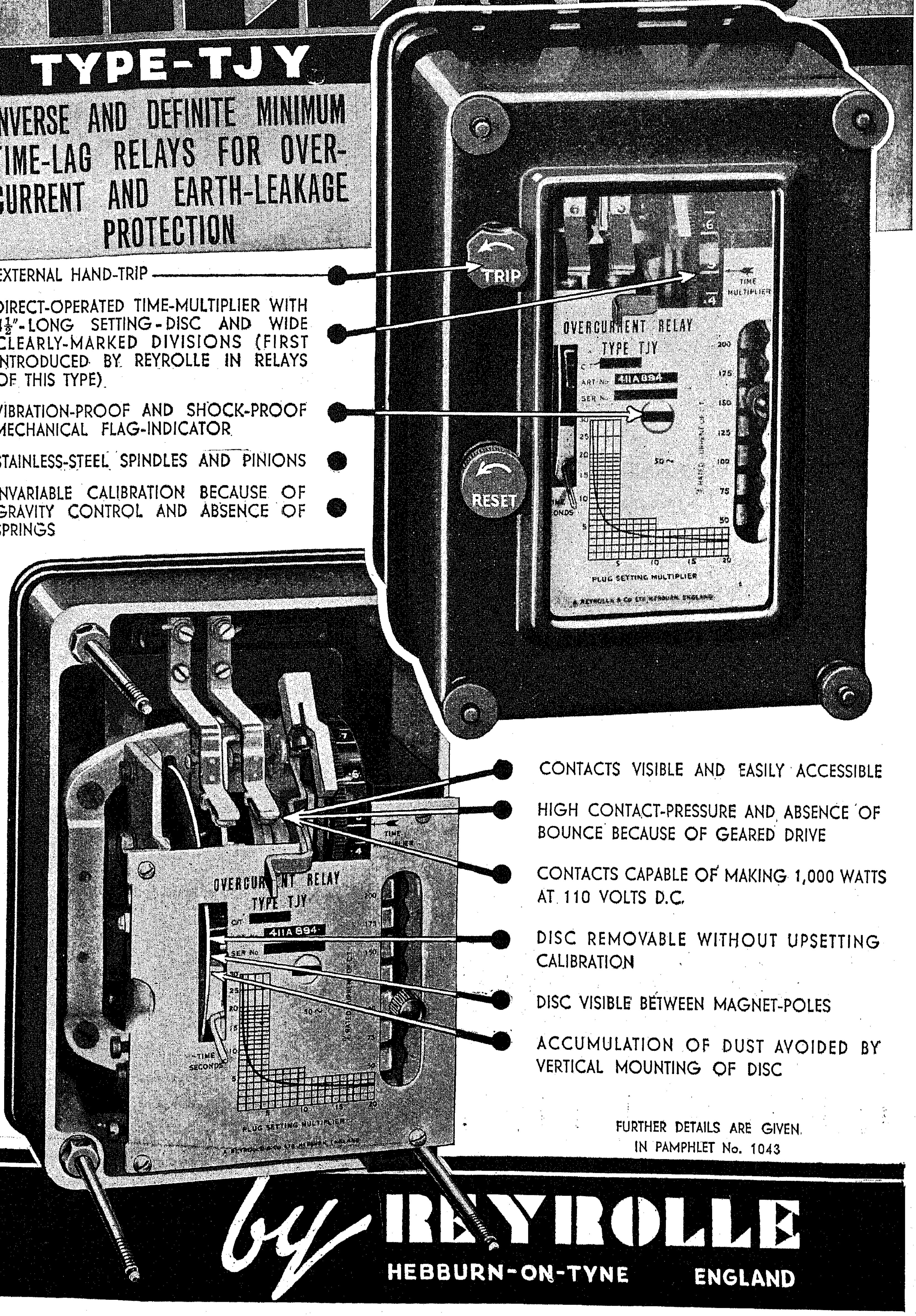

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